NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

EFFECTS OF SENSING CAPABILITY ON GROUND PLATFORM SURVIVABILITY DURING GROUND FORCES MANEUVER OPERATIONS

by

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September 2014

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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** September 2014	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE EFFECTS OF SENSING CAPABILITY ON GROUND PLATFORM SURVIVABILITY DURING GROUND FORCES MANEUVER OPERATIONS	**5. FUNDING NUMBERS**
6. AUTHOR(S) Chung Siong Tng	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words):

The purpose of this thesis is to investigate the effects of sensing capability on ground platform survivability during ground force maneuver operations. Sensor classification probability of ground platforms and speed of unmanned aerial vehicles (UAV) are the factors being studied, and the Map Aware Non-Uniform Automata (MANA) agent-based simulation software was used to create a hypothetical Ground Force Maneuver Operation Scenario for this exploration.

A tailored Waterfall systems engineering process model guided the study in identifying alternatives which, other than increasing armor thickness, can improve platform survivability during ground force maneuver operations. The Nearly Orthogonal Latin Hypercube was the Design of Experiment methodology used to determine the number of design points to be simulated, and the results generated from the multiple simulation runs were analyzed using regression analysis and partition tree analysis.

The sensor classification probability of the Bradley M6 Linebacker and M1A2 Abrams Main Battle Tank, and the speed of UAV, were identified to be the three most significant factors affecting platform survivability. More importantly, the study provides decision makers with quantitative data, which can be used as references to determine the requirements for sensing capability enhancement programs.

14. SUBJECT TERMS Design of Experiment, ground force maneuver operations, UAV, MANA, Nearly Orthogonal Latin Hypercube, platform survivability, Waterfall Systems Engineering Process Model	**15. NUMBER OF PAGES** 127
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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EFFECTS OF SENSING CAPABILITY ON GROUND PLATFORM SURVIVABILITY DURING GROUND FORCES MANEUVER OPERATIONS

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

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ABSTRACT

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LIST OF ACRONYMS AND ABBREVIATIONS

AGM	air-to-ground missile
APFSD	armor piercing, fin-stabilized, discarding sabot
APS	active protective systems
ATGM	anti-tank guide missiles
Corr	Pearson correlation coefficients
Cov	covariance
DOD	Department of Defense
DOE	design of experiment
ERA	explosive reactive armor
FER	force exchange ratio
FO	forward observer
HEAT	high explosive anti-tank
ICV	infantry carrier vehicle
IED	improvised explosive devices
IFV	infantry fighting vehicle
JCA	Joint Capability Area
JMP	JMP PRO V10
KE	kinetic energy
MANA	map aware non-uniform automata
MBT	main battle tank
MOE	measures of effectiveness
MRAP	mine-resistance ambush protected
M&S	modeling and simulation
NOLH	nearly orthogonal Latin hypercube
NPS	Naval Postgraduate School
OA	operation activities
OR	Operations Research
PEO GCS	Program Executive Office Ground Combat Systems
RGB	red green blue color code

RPG-7	rocket-propelled grenade
SAM	surface-to-air missile
SE	systems engineering
TOW	tube-launched, optically-tracked, wire-guided
TTP	tactics, techniques, and procedures
UAS	unmanned aircraft system
UAV	unmanned aerial vehicle

EXECUTIVE SUMMARY

Advancement in weaponry technology and rapid changes in the operation environment have made ground maneuver forces, comprised of armored platforms, more susceptible to attacks. Therefore, there is impetus for the U.S. Army to examine ways to improve the survivability of the land platforms on which soldiers operate and travel. The Mine-Resistance Ambush Protected (MRAP) vehicle is a good example illustrating the efforts made to protect the troops within. The protection concept of improving platforms' passive armor has been proven successful. However, as the focus is on improving protection, lethality and mobility aspects of the platforms are being traded off. Up-armoring platforms is a passive approach, and often the up-armor kits are designed to defend against specific threats and have to be consistently improved to keep abreast with the advancement of weaponry. In additional, existing platforms have almost reached their payload limits, rendering the increase of armor thickness to be a nonviable approach. Such issues provide strong motivation to identify alternative solutions to improve land platforms' survivability.

The author proposes a proactive approach, which studies the effects of improving platform sensing capabilities to increase the survivability of platforms when maneuvering in a hostile environment. Improved sensing capability enables land platforms to identify adversaries faster and gain the advantage to strike first to annihilate the threat sources. In this thesis, unmanned aerial vehicles (UAVs) are modeled to act as additional sensors for ground maneuver forces. Effects of sensor classification probability at maximum range of the various land platforms and the speed of UAVs are examined to determine their effectiveness in improving ground maneuver forces' survivability during operations.

A hypothetical ground force maneuver scenario is modeled using the Map Aware Non-Uniform Automata (MANA) software. The land platforms studied are: the M1A2 Abrams main battle tank (MBT), the Bradley infantry fighting vehicle (IFV), and the Stryker infantry carrier vehicle (ICV). The adversaries, modeled to be in an ambush operation, have similar fighting capabilities, and have fire support from attack helicopters

and 120 mm mortars. The performance parameters for the platforms modeled (agents) are based on open source information and references from theses as exact figures are not available due to classification. Nevertheless, the MANA model is still useful, and the results can be used as a reference to facilitate decision making.

The measures of effectiveness (MOE) identified to address stakeholders' requirement and concerns are Percentage of Blue Casualties and Probability of Mission Success. Both MOEs are able to reflect the survivability of ground platforms during ground force maneuver operations. The analysis found three factors that have significant effects on platform survivability, namely (in order of significance): IFV sensor classification probability, MBT sensor classification probability, and UAV speed. While the results may seem obvious to many, the important findings are the quantitative values of sensor classification probabilities and UAV speeds that can provide decision makers with reference figures to determine the target figures to be achieved. From this study, air defense capability, presence of MBT within ground maneuver forces, and the presence of UAVs are key capabilities that improve ground maneuver forces' survivability.

The systems engineering (SE) approach is used to identify plausible alternatives to improve ground maneuver forces' survivability, and a tailored Waterfall SE process model guided the study. Modeling and simulation are used to analyze one of the alternative solutions identified, effects of sensing capability, on land platforms' survivability. Thirty-three different test configurations were created using the nearly orthogonal Latin hypercube (NOLH) method for design of experiments, and the results obtained from the simulation runs were analyzed using regression analysis and partition tree analysis.

The study on effectiveness of the UAV in this thesis is not exhaustive. The maneuver distance model is only about 20 km. For longer distances, UAVs launched from base would not be able to provide full coverage due to the operating range of UAVs. Hence, one interesting area to be explored would be developing an effective method to launch and retrieve UAVs by ground maneuver forces "on the fly," which may be of interest to the U.S. Army.

The other possible area of research is to incorporate terrain elevation features into the MANA scenario to study the effects of sensor classification probability, sensor detection range, and other sensor attributes. With elevation features added, line of sight of sensors would be affected, and the study could lead to other discoveries.

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ACKNOWLEDGMENTS

First and foremost, I would like to express my greatest gratitude to my thesis co-advisors, Professor Eugene Paulo and Professor Douglas Nelson, for their truthful and illuminating views, valuable guidance, and motivating encouragement whenever I encountered difficulties in this thesis, and to second reader, Senior Lecturer Mark Stevens, for his invaluable advice to this thesis. Without their guidance, I would not have been able to complete my thesis.

I would also like to specially thank Professor Tom Lucas for his willingness to spend time providing me valuable advice on regression and partition tree analysis, and Ms. Mary Macdonald, for her willingness to provide guidance that helped to resolve MANA-related issues, and for her guidance on conducting data analysis using the JMP program.

A special thanks to my family. Words cannot express how grateful I am to my beloved wife, Doris, and two lovely daughters, Chloe and Celeste, for all of the sacrifices they have made, their love, and their encouragement throughout my study here at the Naval Postgraduate School. I would also like to specially thank my brother, Chung Chai, and sister-in-law, Mei Ling, for taking care of my parents while was away for overseas studies. I would also like to thank my parents and parents-in-law for being so supportive of me furthering my studies.

Last but not least, I would like to thank my organization, the Defence Science and Technology Agency (DSTA), for sponsoring my postgraduate studies, and my bosses for nominating me for the DSTA Post Graduate Scholarship Award.

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I. INTRODUCTION

Ground maneuver forces, comprising armored platforms, tracked and wheeled, are becoming more susceptible to attack when they maneuver across hostile environments. Their operating environment changes rapidly as adversaries constantly learn and adjust the way they operate, making it extremely difficult for ground forces to predict, prevent, and stay abreast of the emerging threats. In addition, adversaries have advanced over the years, and may soon reach war fighting capabilities comparable to those of the United States. Therefore, the U.S. Army must examine ways to improve the survivability of ground platforms and protect the lives of soldiers in them. Survivability of platforms is defined as the ability of a platform to avoid or withstand a hit.

A. CONVENTIONAL APPROACH TO IMPROVE PLATFORM SURVIVABILITY

The conventional approach revolves around improving platforms' passive protection to reduce their vulnerability when hit. The ArmorSite details the evolution of the protection system upgrades of the M1 Abrams main battle tank (MBT). From the first version of the MBT to the current version M1A2, protection of the MBT has always been improved to defend the vehicle against evolving threats. In the earlier versions, the approach taken had been adding passive armor to the platform. The Abrams uses composite armor, which is composed of a combination of materials with different types of hardness, elasticity, and heat and shock absorption properties. Little is known on the composition of materials of the composite armor due to classification. The newer versions of the MBT have an additional depleted uranium plate to increase its protection level (Prado 2012). However, the mobility of platforms is reduced when they are mounted with heavy passive armor modules, and the additional weight accelerates the wear and tear of components.

The same trend of adding passive armor can be seen in the Bradley infantry fighting vehicle (IFV) and the Stryker infantry carrier vehicle (ICV). Due to the payload limits of these platforms, passive armor would not be able to provide the same level of protection as it does on the MBT. For example, Stryker can only accommodate slat armor (cage armor), which is much lighter in weight, to defend itself as it cannot take the weight of heavy passive armor modules.

While up-armoring a platform may sound like a simple solution, implementation is not. Extensive and costly modifications, such as replacement of the suspension, transmission, and brake and vehicular control systems, need to be performed. In addition, existing platforms deployed in theater may have reached their maximum payload, making it no longer technically feasible to continue to increase armor thickness.

Active protective systems (APS) and explosive reactive armor (ERA) have also been developed to overcome weight limitations and to further improve platform survivability. As reported in Defense Industry Daily, the Tank Urban Survival Kit, comprised of ERA, for the M1A2 has been developed to enhance the MBT's protection (Defense Industry Daily 2008). There is no open source information on the development of APS for the Abrams. It was reported on the Armored Vehicle website that the Bradley IFV has also been equipped with ERA to enhance its protection (Jones 2014). However, there are concerns about collateral damage to friendly forces in the open when APS and ERA are being activated. Both systems will be discussed in more detail in Chapter III.

The conventional approach is largely passive as it focuses on preventing the platform from being penetrated when hit. It might also take years for the industry to develop the next generation of lightweight and cost-effective passive armor and minimize the degree of collateral damage for APS and ERA systems.

B. THESIS APPROACH

The author adopted a systems engineering (SE) approach to identify plausible approaches, other than the conventional method, to improve the ground platform's survivability when maneuvering in a hostile environment. The focus of this thesis is to analyze the effects of sensor quality (which essentially is the probability and range of classifying targets) on platform survivability when maneuvering in hostile environment. With adversaries also using state-of-the-art weapons, the ability to see first and shoot first is critical. As opposed to the conventional passive approach to reduce vulnerability, the ability to destroy adversaries first before being engaged is an active approach which could improve ground platform survivability. This capability provides platform commanders additional reaction time to make decisions for the next course of action, which is either to evade or defeat the threat before their positions are exposed. Such threats provide strong motivation to examine this area in more detail.

A hypothetical ground force maneuver scenario is modeled using Map Aware Non-Uniform Automata (MANA) software to examine the effects of factors identified on platform survivability. The classes of ground platforms studied in this thesis are the M1A2 Abrams MBT, the Bradley IFV, and the Stryker ICV. The adversaries are designed to have similar ground fighting capabilities. In addition, the effects of employing unmanned air vehicles (UAV) are studied. With the organic ability to scan and perform reconnaissance, the survivability of ground platforms may increase.

C. RESEARCH QUESTIONS

The following are the initial five research questions that guided this thesis. Having gone through the systems engineering process and researches done on the thesis, the author narrowed the list of five questions to the first three. Effects of APS, ERA, and mobility are not modeled and studied in the MANA model developed; therefore, questions four and five are not being addressed in this thesis.

1. What are the primary design factors for ground platforms in order to achieve mission success and survivability in ground force maneuver operations?

2. What are the key sensor attributes that have effects on platform survivability?

3. What are the available mature technologies that have the potential to protect ground platforms against threats that can penetrate through their armor?

4. How would APS improve the survivability of ground platforms?

5. What is the relationship of sensor capability, as well as mobility, to the need for passive armor?

D. CONCURRENT STUDIES

The thesis, which focuses on ground platforms' survivability in ground force maneuver operations, is made in conjunction with two other theses that explore offensive and defensive operations, respectively, in an urban environment. The effects of protection systems such as passive armor, APS and, ERA are being studied in the thesis on offensive operations, and the effects of sensor classification range, mobility and protection systems are being studied in the thesis on defensive operations.

II. BACKGROUND

Ground force maneuver force operations are prone to a wide spectrum of threats, such as 120 mm rounds fired from adversaries' MBTs, anti-tank guided missiles (ATGM), air-to-ground missiles (AGM), and AGM rockets fired from attack helicopters, rocket-propelled grenade (RPG) launchers fired by small pockets of adversary troopers, 120 mm mortar bombs or 155 mm artillery shells, anti-tank mines, and many more.

This chapter describes the threats, the ground platforms studied, and the modeling software used in this thesis. The descriptions are briefly presented to provide readers with some basic knowledge on the items being discussed, and for the ease of reader understanding.

A. THREAT ANALYSIS

This section describes the potential threats ground platforms faced during maneuver operations in hostile environments. The variety of threats presented is not exhaustive, and only the more common ones are being addressed in the simulation model.

1. 120 mm Tank Munition

The two most common types of 120 mm tank munition are (1) the armor-piercing, fin-stabilized, discarding sabot (APFSD), kinetic energy (KE) rounds (which is a high kinetic energy penetrator rod), and (2) the high explosive anti-tank (HEAT) rounds with shaped-charge warheads that have the capability to penetrate through the armor protection of the ground platforms. It has been claimed by the munition manufacturer that both types of 120 mm munitions are capable of penetrating through the thick armor of MBTs (Alliant Techsystems 2011). Both 120 mm munitions have an effective range of approximately 4,000 m (Treml 2013).

2. Kinetic Energy Penetrator Attack Mechanism

The kinetic energy (KE) penetrator uses kinetic energy to penetrate the thick armor of ground platforms. As explained in the article, "Spall Liner: From Fiber to Protection," the killing mechanism for the KE penetrator is the heat, high pressure, and spalling effects as a result of energy transfer during impact and penetration of the armor. Spalls, which are small pieces of material breaking away from a large piece of material, are formed as a result of tension and compression forces that act on the material when a penetrator rod forces its way through the passive armor. The spalls formed with high energy can kill the soldiers and destroy the equipment behind the armor. Figure 1 provides an illustration of spalling when an armored platform is hit by a kinetic penetrator (Bircan, Eksi, and Erbil 2011). The kinetic energy required to achieve such an effect is generated from the propellants in the munition which delivers the munition with an extremely high muzzle velocity that accounts for the high kinetic energy.

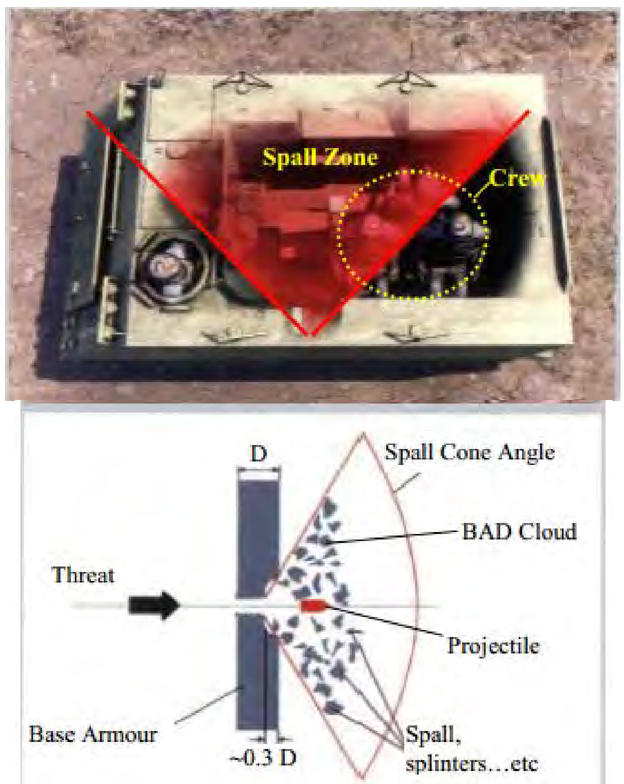

Figure 1. Spall cone and armor penetration without spall liner (from Bircan et al. 2011).

3. High Explosive Anti-Tank Attack Mechanism

The Infantry Rifle Platoon and Squad field manual explains that the attack mechanism of the high explosive anti-tank (HEAT) munition is the penetration through armor protection with a high energy copper jet formed upon impact of the shaped-charge warhead. During impact, the high explosives in the warheads detonate and create a high energy copper jet that can penetrate through the thick armor of ground platforms. Similar to the KE penetrator, spalling occurs as well. Figure 2 provides an illustration of the shaped-charge kill mechanism (Department of the Army 2007).

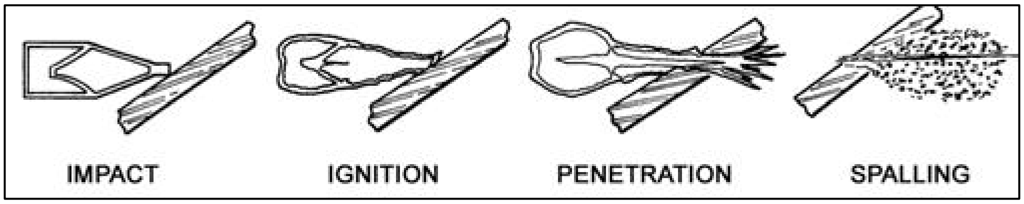

Figure 2. Shaped-Charge Mechanism (from Department of the Army 2007).

4. Anti-Tank Guide Missiles

One example of an anti-tank guided missile (ATGM) is the tube-launched, optically-tracked, wire-guided (TOW) weapon system that has the ability to destroy main battle tanks and other types of armored and soft skin platforms. As stated on the manufacturer's website, the TOW can be a standalone weapon system and can also be integrated onto platforms. Examples of such platforms are the Bradley IFV and the Stryker ICV. The TOW can either be fitted with a HE or HEAT shaped-charge warhead, and the attack mechanism is similar to that of a 120 mm HEAT munition (Raytheon Company 2014). The extended range version, TOW-2B Aero, has an engagement range up to 4,500 m (Chand 2014).

5. Attack Helicopters

Attack helicopters are effective against ground platforms as their weapon engagement range is often beyond the engagement range that ground platforms can easily reach. An attack helicopter also flies at high speed, and Boeing, the manufacturer of the AH-64 Apache attack helicopter, claims that the AH-64 Apache attack helicopter can fly at a maximum cruise speed of about 284kph. Ground attack helicopters can be equipped with air-to-ground (AGM) missiles and rockets which makes them lethal to ground platforms, which usually have poor roof protection. For example, the AH-64's weapon payload comprises laser-guided AGM-114 Hellfire missiles, Hydra-70mm rockets, and M230 30mm automatic cannon (Boeing 2014).

Hellfire missiles have shaped-charge HEAT warheads and are capable of destroying an MBT. These missiles have an operational range between 500 m to 8,000 m (AeroWeb 2014). The Hydra-70mm rocket is also capable of engaging from air to ground and has a maximum range of 10,500 m. It can be fitted with a high explosive warhead that is effective against soft skin platforms, but it lacks precision (Army Technology 2014). Similar to the Hydra-70mm rocket, the M230 30mm cannon is effective against soft skin platforms and troops at a range of up to 4,000 m (Alliant Techsystems Inc. 2011).

6. Rocket Propelled Grenade

The rocket propelled grenade (RPG-7) is a man portable, shoulder-launch, anti-tank weapon. It has a shaped-charge warhead that is capable of penetrating the thick armor of MBTs and other armored vehicles that are less protected than the MBTs. The RPG-7 has an effective range of 500 m (Atronic 2014).

7. Anti-Tank Mines and Improvised Explosive Devices

Anti-tank mines are conventional weapons used against tanks, and there are many types for specific classes of platforms. They have the ability to incapacitate, if not destroy, platforms. Improvised explosive devices IEDs are often used in the same manner, and the only difference between a mine and an IED is the flexibility and ease of manufacturing of IEDs. IEDs can be in different shapes and sizes, making them extremely difficult to detect and classify. Anti-tank mines are mostly passively triggered by pressure on the mine when tanks go over them. IEDs, on the other hand, can be remotely detonated within a short range.

8. 120 mm Mortar Bombs

The 120 mm mortar bomb is fired indirectly on targets. The M120 120 mm mortar has a maximum effective range of 7,200 m (Federation of American Scientists 2000). These bombs fired have high explosive warheads and could probably destroy or incapacitate ground platforms on impact. The base plate positions are typically located miles away, beyond the line of sight of the ground platforms. This makes it extremely difficult for ground maneuver forces to deliver counter battery fire on the mortar positions when ground maneuver forces are not equipped with counter battery fire detection radars.

9. Threat Analysis Summary

For lethality, the focus has generally been on improving weapons engagement range and armor penetration capability. Advances in technology have enabled the development of new weapons capable of engaging targets with higher precision and greater penetration capability. In areas of platform protection, the focus currently is on developing a lightweight protection system with the ability to prevent weapon penetration through the platforms' armor. Unfortunately, development of protection systems requires time and money, and new protection systems must pass through stringent qualification tests before they can be introduced into service. Often protection system developments are reactive and result from new emergent threats that the current protection systems cannot counter. Thus, using the current development model, it is not long after enhanced protection systems are introduced into service that they become obsolete.

B. PLATFORM DESCRIPTIONS

This section presents the specifications of the platforms that are being studied and modeled in this thesis. The specifications of the platforms presented are not exhaustive as capabilities of platforms could be sensitive. The information presented is obtained from open sources available on the Internet.

1. M1A2 Abrams Main Battle Tank

The M1A2 Abrams is the United States' leading MBT, recognized as one of the most powerful platforms of its class. As stated on the website of the original equipment manufacturer, General Dynamics Land Systems, the MBT weighs approximately 70 tons and can travel at a maximum speed of 68 km/hr. Its main armament is the 120 mm smoothbore gun, and its secondary armaments include the 0.5-inch Browning M2 machine gun, a 7.62mm M240 coaxial machine gun, and a loader's 7.62mm M240 machine gun. The Abrams has the capability to defeat platforms of its class and those below it (General Dynamics Land Systems 2014). It is revealed on the Armor Site website that the MBT's 120 mm main gun is capable of engaging targets up to 4,000 m away, and the known protection of the M1A2 includes passive armor and ERA against incoming projectiles, and belly armor against mine blasts (Prado 2012).

2. Bradley Infantry Fighting Vehicle

The Bradley is the United States' IFV. It has the capability of providing protection to the troops being transported in it in a hostile environment, and of engaging adversaries as well. According to the manufacturer's website, the Bradley IFV weighs approximately 34 tons and can travel at a maximum of 61 km/hr. The baseline variant Bradley IFV has a 25mm Bushmaster cannon, which fires both explosive and armor piercing rounds, and a 7.62mm M240 coaxial machine gun. The M6 Linebacker and the Calvary fighting vehicle are the two variants of the Bradley IFV discussed in this thesis. Both variants can be fitted with add-on passive armor to provide the platforms with additional protection (BAE Systems 2014).

The Bradley M6 Linebacker is equipped with four Stinger missiles, which gives it the capability to provide air defense. The FIM-92 Stinger is a surface-to-air missile (SAM) that has maximum engagement range of up to 8,000 m (Federation of American Scientists 2000).

The Bradley Cavalry fighting vehicle, another variant of the Bradley IFV, is equipped with two BGM-71 TOW anti-tank missile launchers, which give it the capability to defeat main battle tanks and other classes of platforms, and carries up to ten (Conner 2014) TOW missiles. The BGM-71 has a shaped-charge warhead, and one of the variants, the TOW-2B Aero, has the highest engagement range of 4,500 m among the variants (Chand 2014).

3. Stryker Infantry Carrier Vehicle

The Stryker is the United States' ICV, and is a wheeled, armored personnel carrier which has the capability to provide protection to the troops in it. Based on the manufacturer's product specifications, the Stryker weighs about 16 tons, and has a maximum speed of 96 km/hr (General Dynamics Land Systems 2014). It was reported on Defense Update that The Stryker can be mounted with slat armor to provide protection against RPGs to increase its survivability (Defense Update 2006). Slat armor is also known as bar armor or cage armor. Of the few variants of the Stryker, the one being analyzed in this study is the Stryker-ATGM variant. The main armament for the Stryker-ATGM is a two-tube launcher for TOW missiles, which has an engagement range of approximately 4,500 m (Chand 2014).

4. Raven Unmanned Aircraft System

According to the manufacturer's product information, the Raven unmanned aircraft system (UAS) is a lightweight portable UAS, and weighs about 2 kg. The light weight allows it to be hand launched. It has an operating range of 10 km, an operating height ranging from 30 to 152 m above ground level, and it flies at a speed range from 31 to 81 km/hr. The Raven is battery operated, and has an endurance of 60 to 90 minutes when rechargeable batteries are used. Its endurance increases to 80 to 110 minutes when single-use batteries are used. The sensor used for aerial surveillance could either be a thermal imager or electro optics, depending on the variant. It can be controlled using a lightweight handheld console (AeroVironment 2014).

5. M198 155 mm Howitzer

The M198 Howitzer is a medium-size field artillery system used by the United States to provide indirect fire support for the U.S. Army. The M198 fires standard 155 mm projectiles and has a maximum effective range of 30,000 m (Federation of American Scientists 2000).

6. Platform Description Summary

Each platform has its own capabilities, which is evident from the weapon systems that are integrated onboard. The Bradley IFV and Stryker ICV are good examples to illustrate this point. Both platforms are designed with multiple variants, each for a specific mission objective. For example, the M6 Linebacker is equipped with Stinger missiles for air defense, and the Bradley Cavalry fighting vehicle is equipped with TOW missiles to take out adversaries' armored vehicles. Information regarding protection systems of these platforms is mostly classified; therefore, open source information about them is limited. However, the general protection design requirements are guided by the types of potential threats that the platform might be exposed to in theater and the payload limitation, which limits the weight of the systems that can be integrated onto the platforms.

C. PLATFORM DESIGN CONSIDERATIONS

Ground platforms provide ground maneuver forces with the defense capability to achieve mission success and provide protection to the soldiers that operate or travel in them. Platform design revolves around three main design traits, namely: Protection, Mobility, and Lethality. The relationships between these three traits are often represented by the "Iron Triangle" of platform design, and designers need to find a balance or optimal design point that adequately addresses them. Due to the specific requirements for each trait, a designer may not be able to enhance all three areas together. Generally, two of the three traits can be improved at the expense of degrading one. But the two being improved would not be at the optimal design point of each of the two traits. See Figure 3 for an illustration of the process of finding the optimal design point in the Iron Triangle of ground platform design.

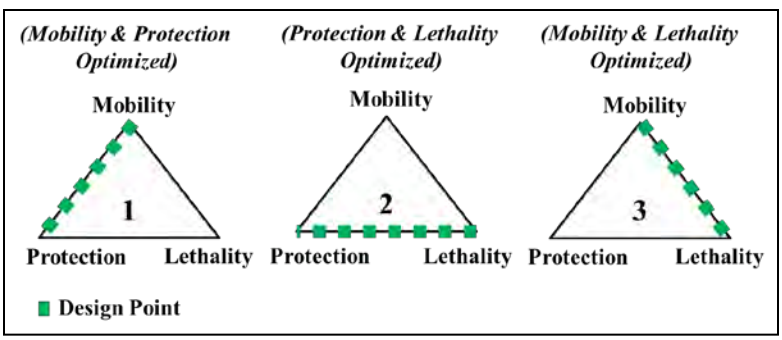

Figure 3. Iron triangle of ground platform design.

The trait to be improved or focused on may be determined by the ground platforms' mission. Once decision makers decide on the traits to focus on, the platform's design will focus on the decided traits. The performances of these three traits are often dependent on the capability of the base platform because the payload threshold usually imposes design constraints. Payload here refers to the weapon and protection systems that can be integrated onto the platform and has a direct effect on the platform's mobility.

Each of the three traits of platform design has a direct impact on the survivability of a ground platform. A platform with high mobility provides the platform the ability to evade incoming projectiles, the ability to maneuver in terrain where the adversaries least expect, and the ability to quickly maneuver out of the danger zone, making it more difficult to be tracked by adversaries. Therefore, the platform should be highly mobile. Lethality provides the platform with the ability to take down targets, which eliminates the threat source that can inflict damage or destroy the platform. Hence, the lethality of a platform can also serve as a form of deterrence to adversaries. From this perspective, lethality also indirectly improves platform survivability. Lastly, protection is directly linked to platform survivability. A more protected platform will have higher survivability. The latter two often reduce platform mobility due to the increase in weight when more systems are integrated onto the platform.

This focus of this thesis is to identify factors other than increased armor protection to improve platform survivability, and the MANA software is used to model the operational scenario which facilitates the study on the parameters that would affect platform survivability.

D. AGENT-BASED MODELING SOFTWARE – MAP AWARE NON-UNIFORM AUTOMATA (MANA)

The MANA software is an agent-based, time step, stochastic, mission-level simulation model developed by the New Zealand Defence Technology Agency. The MANA user manual provides users with the understanding of how effective MANA is, and how to use it. MANA can be used to model and study military operation scenarios. The agents created in MANA are *map aware*, which means they are capable of interacting with the terrain and surroundings created in the operational scenario with their sensors, and react according to their behavior attributes settings. The agents are *non-uniform*, which means they can be modeled individually. *Automata*, which means agents behave based on their behavior attribute settings, are independent of the scenarios.

Behavioral attributes refer to the way agents move, sense, shoot, and communicate according to the situation of the individual agents (Anderson et al. 2007).

III. SYSTEMS ENGINEERING APPROACH

Systems engineering is a field that analyzes, solves, and manages complex problems. The process follows structured steps, adopts a holistic approach to address customer's needs, and analyzes the required functionality, systems requirements and systems supportability throughout the entire lifecycle in the early stage of the project.

A. SYSTEMS ENGINEERING PROCESS MODEL

The author modified Winston W. Royce's Waterfall SE process model, developed in 1970, and tailored it to guide the study of this thesis (Blanchard and Fabrycky). The tailored Waterfall model is presented in the Figure 4. The model is iterative, and each phase of the model can provide feedback to any of its preceding phases. The model starts with Threat Analysis to collect information, understand the threats, and analyze the capabilities of the ground platforms studied in this thesis. That sets the stage for the Problem Definition phase, which identifies the current capability gaps and the desired future situation. Stakeholders Analysis is also done at this stage to identify their primitive needs. The process then moves on to operational analysis, functional analysis, and analysis of alternatives. The selected alternatives will be modeled using MANA simulation software, and the data generated will be analyzed to find out the response to the changes made to the variable. Details of each stage of the systems engineering process are presented and discussed in subsequent chapters.

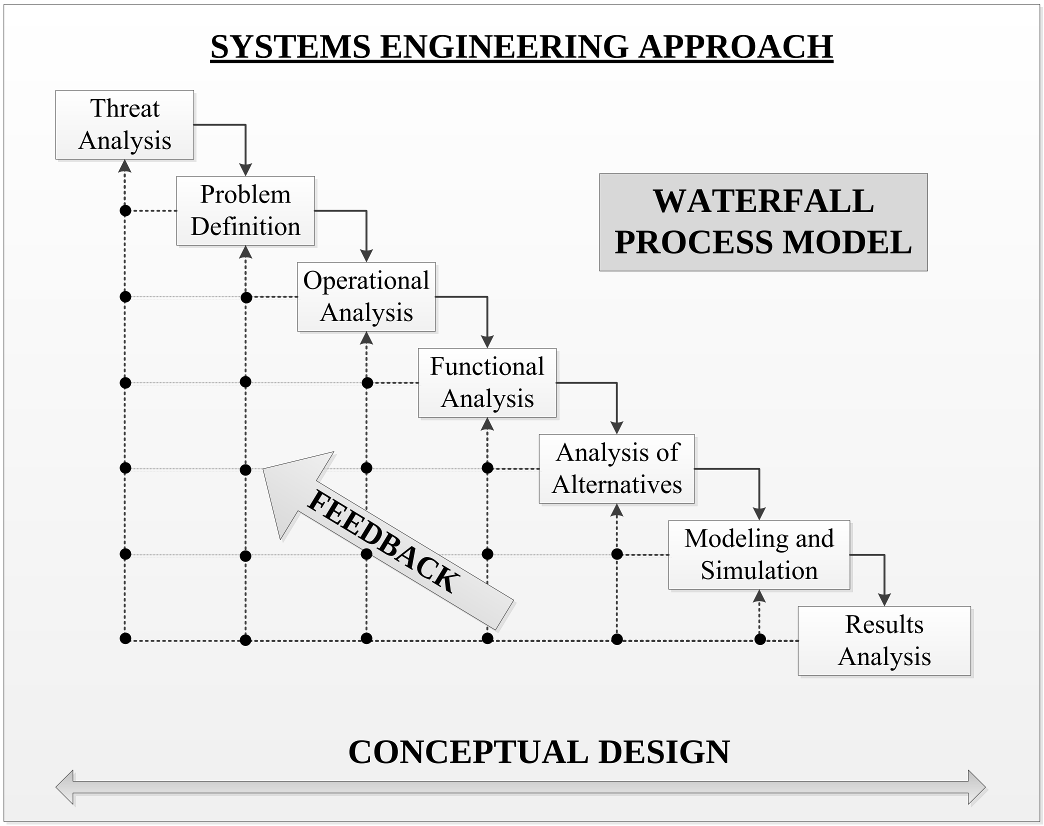

Figure 4. Tailored Systems Engineering Waterfall Process Model.

B. PROBLEM DEFINITION

Advancements in technology have created weapons that are far more lethal than they used to be. The conventional approach of increasing passive armor thickness on ground platforms may not be the way ahead as advancements in weaponry are going at a faster pace than armor protection development. Adding to the difficulty of protecting against increasingly lethal weapons, most existing platforms are reaching their weight limits, making it technically not feasible to keep adding passive armor thickness. This weight limit, the platform's maximum allowable total weight, is determined by its superstructure, suspension, transmission, and braking and other supported systems. Therefore, there is a need to identify other approaches to improve ground platforms' survivability while developments in armor protection are still in progress. Systems engineering, which is a structured approach to analyze systems and solve problems, is the approach that allows the exploration of alternatives to improve a platform's survivability.

The solutions could be near term or long term, and a wider variety of survivability enhancement options may evolve.

C. CURRENT CAPABILITY GAPS

Currently, ground platforms are unable to adequately protect themselves and the soldiers operating in them against large caliber munitions such as the 120 mm KE and HEAT munitions. This section discusses the technology challenges faced and the inherent limitations of ground platforms in improving these platforms' survivability. Weight limitations and existing platform design are the inherent limitations of ground platforms identified. Technology challenges include the effectiveness and concerns to integrate ERA and APS into existing platforms. Lastly, battlefield situation awareness level of ground platforms is identified as one of the capability gaps that need to be bridged to improve ground platform survivability.

1. Weight Limitation

Existing ground combat platforms are almost reaching their maximum weight limits, and increasing passive armor thickness to defend against incoming projectiles will soon be a non-viable solution. Equipping platforms with all-round protection is becoming too heavy for even main battle tanks to support. The 120 mm kinetic energy munition still remains as a great threat to passive armor. Protection systems such as ERA and APS have been developed, and we have seen some main battle tanks being installed with ERA; however, little is known about platforms that are installed with APS.

2. Protection Systems – Explosive Reactive Armor (ERA)

ERA is a type of armor that is comprised of explosives sandwiched between two metal plates. As presented in a study done on disturbance of ERA by jet penetration, when an incoming projectile hits the ERA, the explosives are detonated and two metal plates are pushed out by the explosives, which break the flight path and reduce the energy of the incoming projectile causing it to lose its penetrating capability (Li, Lv, and Yan 2014).

ERA is effective against HEAT munitions, and some companies claim that their ERA is capable of defeating KE penetrators, which has yet to be proven. However, like slat armor, ERA is quickly defeated by projectiles with tandem warheads. Tandem warhead projectiles have two shaped-charges within the same warhead. The first shaped-charge detonates the ERA, and the second shaped-charge simply penetrates the bare armor beneath the ERA with ease and destroys the platform, including the personnel within. Although ERA can be stacked together to protect against tandem shaped-charge warheads, the weight limit of the platform often does not allow the doubling of ERAs. Development of ERA is ongoing, and it will probably take a while until they are fully developed. There are also concerns on collateral damage.

3. Protection Systems – Active Protective Systems (APS)

Rafael Advanced Defense Systems claims that their APS when integrated with ground platforms has the ability to detect incoming projectiles and fire a counter munition to successfully defeat or break the path of the incoming projectile. Furthermore, this APS is able to provide the platform with 360-degree protection against single or multiple incoming projectiles. (Rafael Advanced Defense Systems 2014).

It is not publicly known which countries have installed such systems on their platforms. However, there are two common concerns related to APS. One is their ability to stop KE penetrators due to their high incoming speed, and the other is collateral damage to own troops, especially when there are troops in open or in soft-skin platforms. Little technical information on the APS can be found in open sources. With APS installed, there might still be a need to equip platforms with passive armor or ERA as a secondary protection layer to defend against leakers (incoming threats that are not defeated by APS or ERA). Again, keeping within the weight limits may pose challenges to platform designers. Unlike ERA, which requires mainly mechanical modification, APS integration requires both electrical and mechanical modifications.

4. Ground Platform Roof Protection

Protection for ground platforms has always been focused on side, frontal, rear, and belly protection. Comparatively, there is little focus on roof protection. One possible reason for this could be the low probability of air attack in the past when the platforms were developed. Hence, traditionally roof protection has not been the area of focus. To improve roof protection for existing ground platforms, the structural strength of the platform must be studied to determine whether the structure can take the weight of the heavy passive or ERA protection modules. The addition of protection modules to the roof of platforms might lead to other integration issues such as increased dead ground (areas blocked from crew observation) for platform commander and driver, or obstructed turret slew. When dead ground increases, the area which the driver and commander can see from their position decreases, making it more difficulty for the driver to drive, and for the commander to guide the driver.

5. Battlefield Situation Awareness

Battlefield situation awareness of ground platforms is limited by their line of sight, making them very vulnerable to long range attacks such as: artillery firing and missiles fired from attack helicopters. Engagement ranges of such adversaries' weaponries provide the advantage to engage ground forces from locations that are beyond their lines of sight. Although the platforms have combat management systems that will map out the locations of threats discovered by other sensors, these platforms are not able to engage the target before being engaged due to no line of sight. Although ground platforms can rely on supporting units from other services to provide situational awareness, support units may not be readily available. The mission might still need to proceed even without external support, making the ground platforms more susceptible and vulnerable.

D. DESIRABLE SITUATION

It is desirable for ground platforms to be equipped with 360-degree protection against advanced weaponry to improve their survivability. While the development of protection systems is still ongoing, there is a need to explore and develop stopgap measures. Additionally, employing UAVs as sensors, coupled with indirect cover fire support, would greatly enhance ground platforms survivability during maneuver operations. Having the UAVs as organic assets would reduce the reliance on other services.

E. CONSTRAINTS IDENTIFIED

The constraints identified are: (1) existing platforms reaching their weight limits, (2) development of new protective armors such as lightweight passive armor, and (3) sensing limitation of ground platforms.

F. STAKEHOLDER ANALYSIS

Stakeholder analysis identifies the parties that have interests in the problem, and allows the systems engineer to find out and analyze their needs. This section lists the stakeholders and their descriptions in terms of their power of influence and their level of interest in ensuring that ground platforms are highly survivable during operations, which eventually leads to mission success.

1. Identifying Stakeholders

Five stakeholders have been identified and ranked in order of priority, and the prioritization methodology is based on their power of influence and level of interest. The stakeholders are: (1) U.S. Department of Defense (DOD), (2) U.S. ARMY, (3) Program Executive Office Ground Combat Systems (PEO GCS), (4) U.S. Congress, and (5) Defense Industries.

2. Stakeholder Description and Analysis

The U.S. DOD's mission is to provide the military forces needed to deter war and to protect the security of the United States (DOD 2014). The DOD is the main stakeholder, and being the decision maker, DOD has the highest power of influence and level of interest to ensure that ground platforms are adequately protected against incoming threats fired from adversaries, which is closely aligned to their mission statement. Their concern would be how to acquire new and effective protection capabilities in the shortest possible time to bridge the U.S. Army's capability gap.

The U.S. Army, being the direct user of ground platforms, is aware of the lethality of the types of threats and understands areas that need to be improved to enhance platform survivability. The U.S. Army Equipment Modernization Strategy captures the organization's key operational priorities of which "remaining prepared for decisive action by increasing lethality and mobility, while optimizing the survivability of our vehicle fleets is one of the areas of focus" (Mchugh and Odierno 2014). Therefore, they have significant influence over the types of protection systems to be integrated onto the ground platforms. The U.S. Army also has a high level of interest as a better protected platform minimizes casualties and increases mission successes. Their troops currently in theater are facing a wide spectrum of threats, and the U.S. Army would like to equip them with effective protection capabilities to protect these troops as soon as possible. Their current stop gap measure is to constantly review their tactics, techniques, and procedures (TTP) to stay abreast of the rapid changing operational environment.

The Program Executive Office Ground Combat Systems (PEO GCS) is the acquisition branch of the U.S. Army, and is responsible for providing world-class affordable, relevant, and sustainable ground combat equipment to Joint Warfighters. The systems under PEO GCS' purview include the Abrams main battle tank, Bradley family of vehicles, towed and self-propelled howitzers, Stryker family of vehicles, robotics and unmanned ground systems (PEO GCS 2014). Being at the technological forefront of the U.S. Army, they possess a high power of influence over the protection systems that are suitable for ground platforms as they are the ones who will test and evaluate the suitability of various types of protection systems proposed by suppliers. They also have a high level of interest in ground platform survivability as one of their roles is to incorporate lethality, survivability, mobility, and adaptability improvements of ground combat vehicles for the warfighter.

The U.S. Congress is the next main stakeholder in the topic of interest of this thesis. As the sponsor for all military programs, the Congress has a high power of influence over military expenditures. Being the legislative branch of the federal government, they are responsible and accountable for the money spent on defense (CongressLink 2014). Therefore, one of their roles is to ensure prudent spending.

The defense industries are the developers of the protection systems. They influence the designs of the type of protection systems that can be integrated onto ground platforms. Their level of interest would be high since this is a profitable business area and would help them boost their reputation in the marketplace if their systems are being used on U.S. ground platforms.

To summarize, stakeholders need their ground platforms to be adequately protected against advanced weaponry faced in theater to protect troops operating on or transiting within the platforms during operations to increase mission success probability. Any proposed solution need(s) to be cost effective, and if it is a long-term solution it would take a while before implementation. Therefore, stopgap measures should be available. Having analyzed and identified the needs of stakeholders, the next phase in the systems engineering process model, Operational Analysis, will be presented.

G. OPERATIONAL ANALYSIS

Ground maneuver forces are required to perform a wide range of operations which for ease of understanding can be classified into Offensive, Defensive, and Maneuver Operations, and the focus of this thesis is on Ground Force Maneuvers.

In the Joint Capability Area (JCA) 2010 refinement paper, JCA 3, Force Application, is defined as the ability to integrate the use of maneuver and engagement in all environments to create the effects necessary to achieve mission objectives. Maneuver, as defined in JCA 3.1, is the ability to move to a position of advantage in all environments in order to generate or enable the generation of effects in all domains and the information environment. Maneuver is further subcategorized into four categories namely, Maneuver to Engage, Maneuver to Insert, Maneuver to Influence, and Maneuver to Secure (J7 Joint Force Development and Integration Division 2011).

A hypothetical scenario for a ground forces maneuver operation has been created for the purpose of this study and is described here.

1. Generic Ground Force Maneuver Operations Scenario

The operational scenario, shown in Figure 5, is to maneuver Blue forces comprising a company of Abrams MBT, a company of Bradley IFV, and a company of Stryker ICV from base camp to a designated location. It is anticipated that there are adversaries (Red forces) in ambush along the movement route. The maneuver operation force is broken down into three teams at intervals of ten minutes, and the formation of each team is in the following order: MBT followed by IFV and lastly ICV, each with a platoon size.

The type of MBT and ICV are the same for all three teams, and for the IFVs, with the first team of IFV comprising M6-Line Backers and the remaining two comprising Bradley ATGM variants. The rationale is to provide the first team, also known as Advance Platoon, with air defense capabilities. Fifteen minutes prior to moving out, two units of Raven UAVs will be deployed for aerial surveillance. When Red forces are spotted by the UAVs, artillery fire will be activated to neutralize the threats. An M198 155 mm Howitzer platoon will be providing cover fire for the maneuver operation. Red forces are modeled to comprise 120 mm mortars, attack helicopters, anti-tank mines, troops with RPG-7, soft-skin trucks with anti-tank guided missiles and MBTs.

Figure 5. Generic Ground Force Maneuver Operations (from Google maps 2014).

2. Operational Activities for Ground Force Maneuver Operations

The operational view (OV)-5b model of the DODAF Framework Version 2.02 is used to describe the operational activities (OA) that are conducted within the ground force maneuver operations. OA are the work that must be done, and by mapping out the OA, the required functions can be identified (DOD 2010).

OV-5b, presented in Figure 6, illustrates the Level-1 OA needed to perform ground force maneuver operations. The maneuver mission starts with OA1.1, launching UAVs to execute area surveillance. During this OA, outputs such as images will be transmitted back to headquarters for processing. The next OA, OA.1.2 to OA.1.4, would be ground platform teams transiting to the destination at ten-minute intervals. During maneuvers, the platforms will be communicating battlefield situation updates with headquarters. Concurrently, OA.1.5, 155 mm artillery will be providing cover fire for the maneuvering forces throughout the entire mission. They will be triggered to fire once upon receiving firing instructions. Each Level-1 OA will be further illustrated down to Level-2 OAs in subsequent sections.

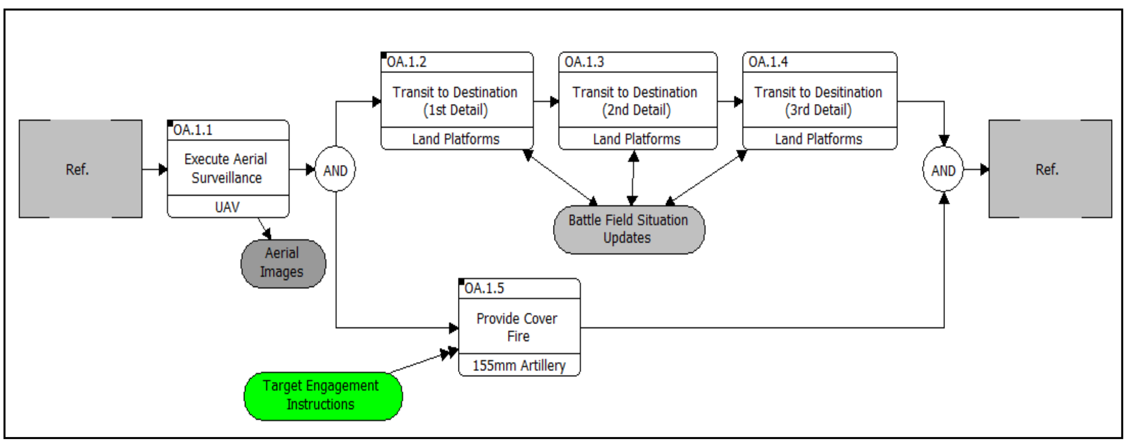

Figure 6. OV-5b Operational Activity.

a. *OA.1.1 Execute Aerial Surveillance*

Figure 7 illustrates OA.1.1. The UAV will be launched 15 minutes prior to the ground platforms to sense threats. When launched, the UAVs can either follow pre-determined waypoints to capture images of the environment to be sent back to headquarters for processing and to the combat management systems onboard the ground platforms or follow new flight instructions. Flight instructions could be to hover around targets when detected or take a different flight path.

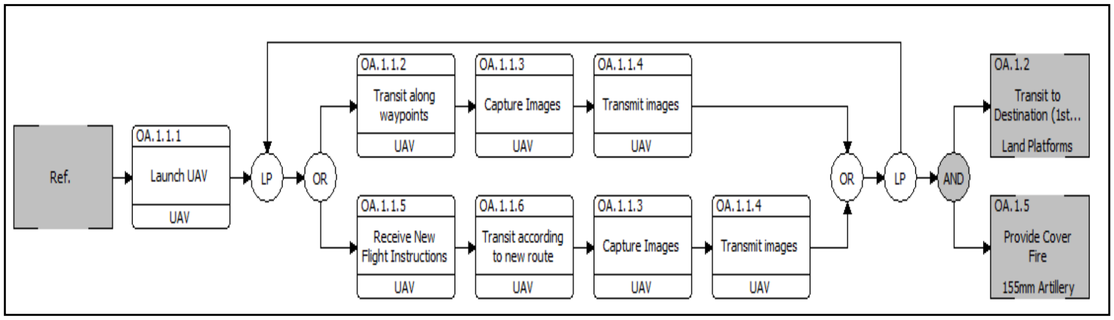

Figure 7. OA.1.1 Execute Aerial Surveillance.

b. OA.1.2 Transit to Destination

Figure 8 illustrates OA.1.2. Fifteen minutes after the deployment of UAVs, the ground platforms will commence ground force's maneuver operations. During transit, the platforms will constantly be scanning for threats, and communicate with headquarters for updates of the battlefield situation. When adversaries are sighted, the ground force will employ weapons to engage them. In the absence of threats, ground platforms will continue to maneuver to their destination. The sequence of activities for OA.1.3 and OA.1.4 are the same as OA.1.2.

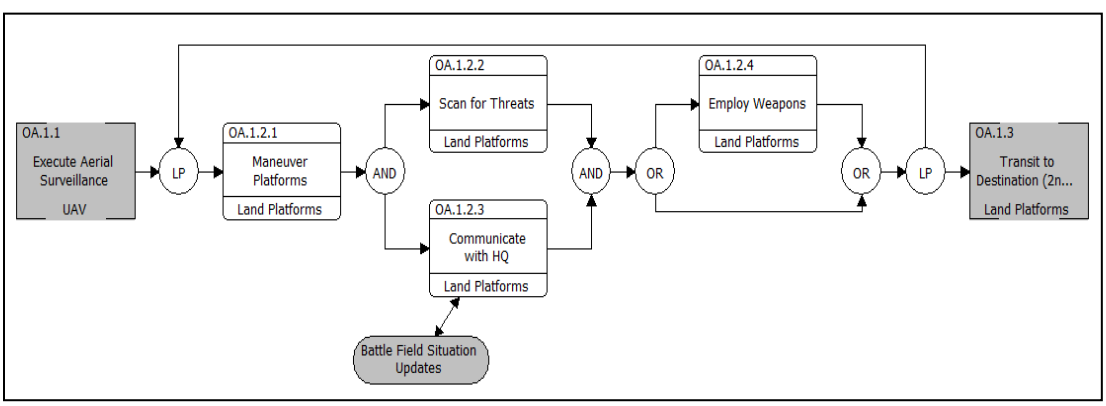

Figure 8. OA.1.2 Transit to Destination.

c. *OA.1.5 Provide Cover Fire*

Figure 9 illustrates OA.1.5. When the UAVs are deployed, the 155 mm artillery unit is on standby waiting for targeting instructions. Once instructions to engage the target are received, the weapons (155 mm artillery) are positioned and employed to engage the target. Upon successful destruction of targets, a situation report will be updated to headquarters.

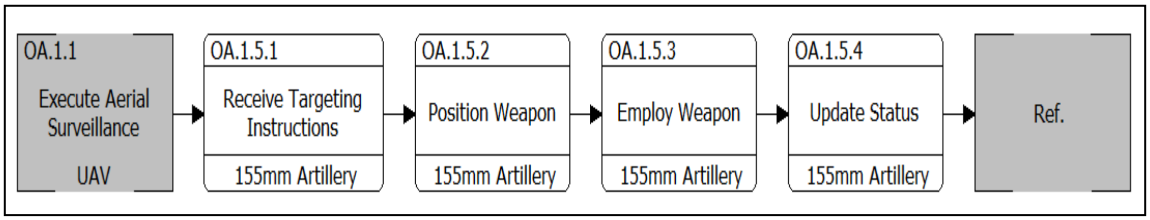

Figure 9. OA.1.5 Provide Cover Fire.

H. GROUND MANEUVER FORCES CONTEXT DIAGRAM

The context diagram presented in Figure 10 depicts the ground platforms' interaction with external elements in their operating environment. Analyzing the context diagram allows the identification of types of interactions and the resources being transferred between the ground maneuver forces and the external elements.

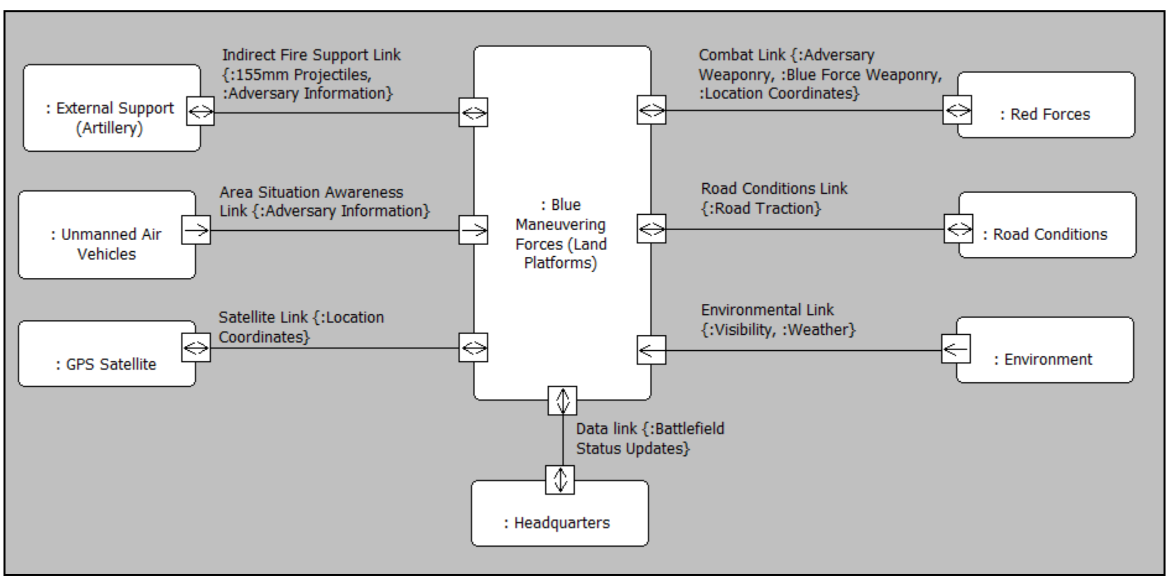

Figure 10. Context Diagram (Blue Maneuvering Forces).

1. Elements Description

The elements will be explained starting from the left and moving downwards, followed by moving from the right and downwards.

(1) External Support (Artillery)

The M198 155 mm howitzer provides covering fire for the ground maneuvering forces. The link between them is an indirect fire support link.

(2) Unmanned Air Vehicles

The UAVs are the additional sensors to the ground maneuvering forces. This link is the communication link where the images captured by the UAVs are being transmitted to the combat management system in headquarters and to the platforms.

(3) Global Positioning System Satellite

This is the link on which the onboard Global Positioning System (GPS) receiver obtains the position coordinates of the ground platforms to determine their own location.

(4) Headquarters

This is the information exchange link for maneuvering forces to communicate with headquarters (HQ) on the latest updates on the battlefield.

(5) Red Forces

This is the combat link between the Blue and Red forces. The link is physical as there are munitions exchanged during engagements. The link is also a non-contact link when information such as location data, physical appearance, signature, and characteristics of each party are being exchanged.

(6) Road Conditions

This is the road condition when the ground platforms are transiting to the destination. The road conditions link is physical, providing road feedback through contact between ground platforms and the road, affecting the traveling speed.

(7) Environment

This is the weather link during operations. The environmental link provides environmental information, such as temperature, wind direction, rain, and humidity readings to the ground platforms.

With the operational scenarios and context diagram analyzed, the next step would be to perform function analysis to identify the functions of the ground platforms for ground force maneuvering operations.

I. FUNCTIONAL ANALYSIS

A function is an action performed to achieve a desired outcome, and in the defense context, usually the function is mission objectives. Functional analysis looks into what a system is supposed to do, and not how the system will be doing it. Often engineers tend to approach the problem from a solution-based mentality which narrows the exploration of other viable approaches to solve a problem. Focusing on functions widens the solution space and promotes exploration and analysis of multiple alternatives.

1. Functional Decomposition

The analysis method for functional analysis is functional decomposition. Functional decomposition first identifies the high-level critical functions that are required to be performed by the system to achieve the objectives. Each high-level function is then further decomposed into its sub-level functions, which are more specific. This approach simplifies a complex problem by breaking up the problem into smaller manageable portions, which are easier to resolve.

Figure 11 illustrates the functional decomposition of the high-level function labeled Maneuver Ground Forces. During maneuver operations, the OAs are: Maneuver Platform, Scan for threats, Communicate with HQ, Employ Weapons, Provide Protection, and Receiving Battle Field Status updates. From these activities, the six critical functions identified are: Move Assets, Sense Adversaries, Protect Crew, Attack Adversaries, Communicate Information, and Monitor Area of Operations. Details of the critical functions and sub-level functions will be discussed further in this section. For this thesis, the functions are decomposed to the second level only. A description of the functions is provided in Table 1.

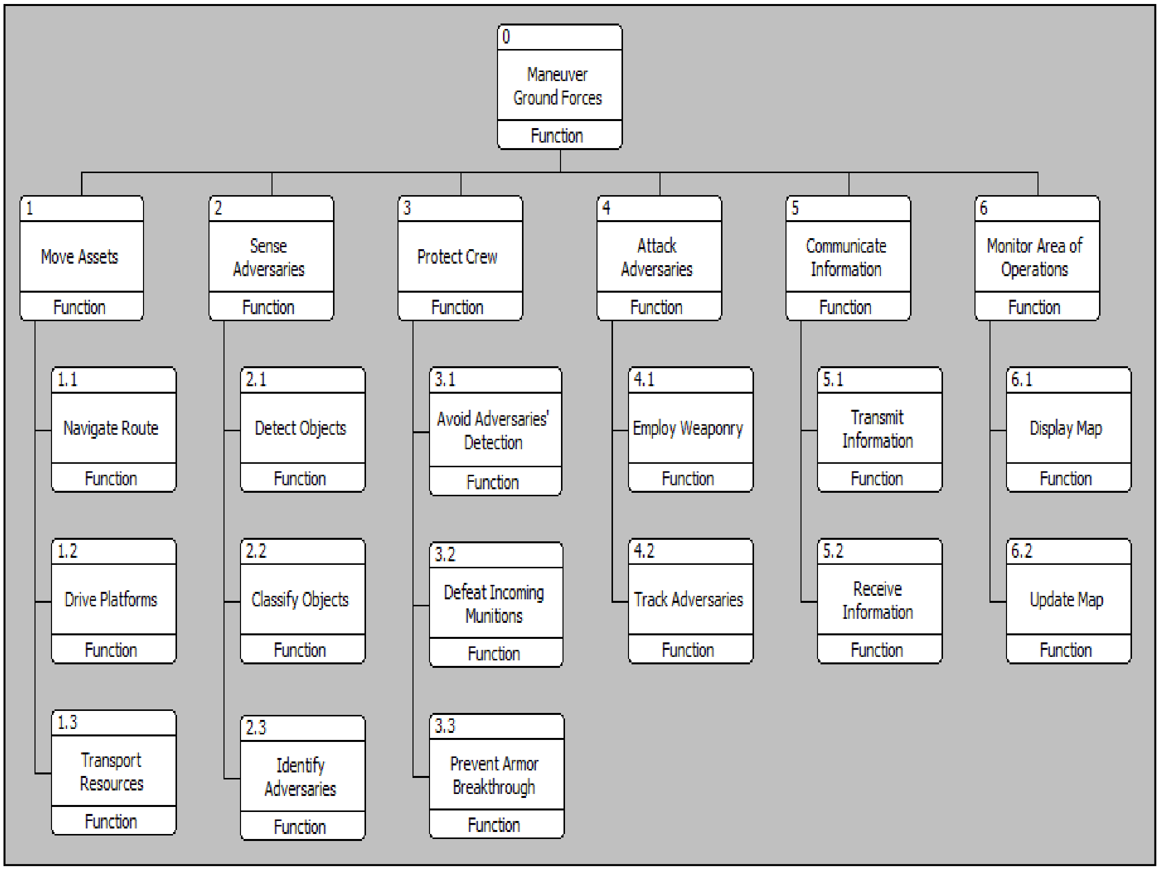

Figure 11. Functional Decomposition.

Table 1. Functions Descriptions.

Functions	Descriptions
0. Maneuver Ground Forces	Maneuver ground platforms across hostile or unknown terrains.
1. Move Assets	Move assets physically from base to destination. Assets refer to the platforms, troops, equipment, and logistics supplies.
1.1. Navigate Route	Provide driving route directions for platforms to move from base to destination. The next level of sub-functions may include Determine Own Location, Plan Route, and Display Route, etc.
1.2. Drive Platforms	Control platforms. The next level of sub-functions may include Go Forward, Go Backward, Steer Direction, Stop Platform, etc.
1.3. Transport Resources	Move resources from base to destination. Resources include troops and logistic supplies. The next level of sub-functions may include Provide Seats, Store Items, Secure Items, etc.
2. Sense Adversaries	Keep a look out or search for adversaries while maneuvering within area of operations.
2.1. Detect Objects	Spot objects at a distance away.
2.2. Classify Objects	Determine the type of objects detected.
2.3. Identify adversaries	Differentiate objects classified between friend or foe.
3. Protect Crew	Prevent crew from injury or death.
3.1 Avoid Adversaries' Detection	Prevent the ground platforms from being detected and targeted. The next level of functions may include Reduce Platform Signature, Camouflage Platforms, etc.
3.2 Defeat Incoming Munitions	Prevent munitions from hitting the platforms. Munition refers to projectiles, penetrator rods, warheads, etc. The next level of functions may include Detect Incoming Munition, Classify Incoming Munition, Compute Countermeasure, Employ Countermeasure, Display Warning Signals, etc.
3.3 Prevent Armor Breakthrough	Prevent munition from penetrating through the armor, killing troops within, and destroying the platform when being hit. The next level of functions many include Stop Penetration, Deflect Munition, etc.
4. Attack Adversaries	Destroy adversary platforms, troops, or equipment.
4.1 Employ Weaponry	Use onboard weapons to destroy adversaries. The next level of functions may include Fire Weapon, Reload Weapon, Conduct Battle Damage Assessment, etc.
4.2 Track Adversaries	Maintain sight on adversaries identified. The next level of functions may include Follow Adversaries Movement, Compute Adversaries Speed, Determine Distance, Compute Firing Settings (direction and elevation angle), etc.
5. Communicate Information	Exchange information among own forces.

Functions	Descriptions
5.1 Transmit Information	Send information across wireless network. Information refers to data, images, or voice messages. The next level of functions may include Establish Communication Link, Encrypt Information, Send Information, etc.
5.2 Receive Information	Obtain information from radio frequency network. Information refers to data, images, or voice messages. The next level of functions may include Establish Communication Link, De-Encrypt Information, Project Information (voice messages or images), etc.
6. Monitor Area of Operations	Provide battlefield situation awareness.
6.1 Display Map	Provide visual image of map of operation environment with location of own forces and adversaries spotted.
6.2 Update Map	Process information received and update location of own forces and adversaries when there are any changes.

After identifying the functions of the systems, the requirements definition can be analyzed and determined. In addition, the outputs of functional analysis facilitate the generation or exploration of design alternatives.

The purpose of this thesis is to study the effects of alternatives to improve platform survivability. Therefore, requirements analysis will not be done in this thesis. The next chapter studies the alternatives that are available to improve the survivability of ground platforms.

J. ANALYSIS OF ALTERNATIVES

There are two approaches to improve the survivability of the ground platforms. The author generally classifies the alternatives into two types, namely: the passive approach and active approach.

The passive approach employs countermeasures when the platforms are being fired upon. Protection systems such as passive armor, explosive reactive armor, and active protection systems are examples of the passive approach to protect the ground platform. The similarity in them is that the adversaries have already fired at the ground platforms, and the munitions are on their flight path toward the ground forces. So it is the effectiveness of these protection systems in responding to the incoming munitions that will affect the platform's survivability.

Another passive approach would be to improve the mobility of the ground platforms. A high mobility platform has a higher chance of evading incoming munitions when being fired at. High mobility also makes it harder to be engaged.

The active approach employs countermeasures to engage adversaries first before ground forces are engaged. The following are some alternatives that can be considered.

1. Signature Management

Avoiding being seen can be achieved by integrating stealth technologies such as camouflaging the platforms using some specialized paint to alter the infrared signature of the platform. This measure allows the platforms to blend in with their surroundings, making it difficult for them to be seen on thermal imagers. Modifications to reroute exhausts is another way to change the heat signature of the platform, and this increases the difficulty of being detected and classified by thermal imagers.

2. Sensing Capability

Another active approach alternative is to improve the lethality of the platform. When ground maneuver forces meet adversaries with almost equivalent lethality, the determining factor would depend on who can see and shoot faster. Without changing the weaponry of the platforms, increasing the speed of the ground platform's sensing capability could increase the success in engaging an adversary first. Speed of sensing can be a function of the detection range, object classification probability, and identification probability. The further the detection range, the earlier an object can be detected. A higher probability of object classification and identification reduces the time required to determine the type of object that has been detected and whether the object is friend or foe. Employing UAVs as sensors for ground platforms enhances the sensing capability of ground maneuver forces, giving them better situation awareness and more planning time to respond to changes in the operational environment.

3. Battlefield Management System

Having updated information on what is happening in the operational environment allows commanders on the ground to better plan the next course of action and improve mission success and reduce attrition. This is achievable with a robust, secure, and fast communication network.

4. Potential Scope of Analysis on Survivability Improvement

Figure 12 presents the potential areas that can be explored and analyzed for their effects on platform survivability.

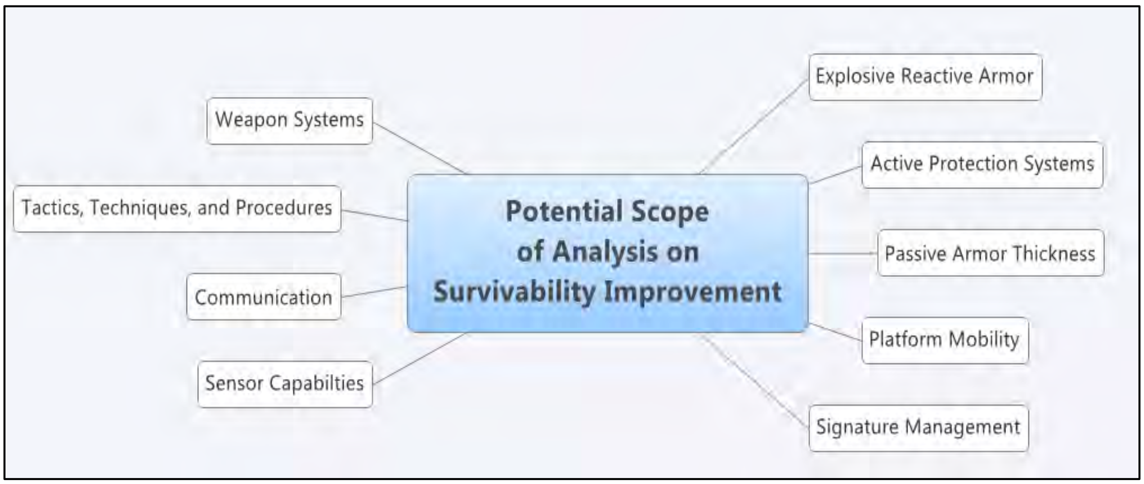

Figure 12. Potential Scope of Analysis on Survivability Improvement.

The author's intent is to explore alternatives to improve platform survivability. The alternatives should not cause a significant increase in the weight of the platform, as existing ones are already reaching their weight limits. Furthermore, the alternatives should not require significant modifications, and should be able to be modeled in MANA simulation software for high fidelity. Battle tactics related alternatives are not studied, as the focus of this thesis is on technologically feasible solutions.

Effects of Explosive Reactive Armor, Active Protection System, and Passive Armor Thickness may potentially result in exceeding the weight limits of existing platforms. Weapon Systems, Platform Mobility, and Signature Management may require significant modifications.

Thus, between communications and sensor capabilities, the author chooses to explore the area of sensor capabilities as the effects of communication have been previously studied in another Naval Postgraduate School (NPS) thesis, "Determining Intelligence, Surveillance, and Reconnaissance System Effectiveness and Integration as Part of Force Protection and System Survivability" (Soh 2013). Within the scope of the study defined, the next chapter presents the Alternatives Analysis Methodology used.

IV. ALTERNATIVES ANALYSIS METHODOLOGY

Use of the systems engineering approach helped identify various alternatives that could potentially resolve the problems identified in the previous chapter. However, not all alternatives are effective and need to be analyzed. Methods such as modeling and simulation, evaluation of the technical specifications, rapid prototyping, analyzing past data, and comparing these methods against other similar systems can be used to analyze the effectiveness of the alternatives. Each of the methods has its own advantages and disadvantages. Therefore, the suitability of the analysis approach must be considered.

A. MEASURES OF EFFECTIVENESS

Prior to determining which analysis approach to adopt, the measures of effectiveness (MOE), which measures the effectiveness of the alternatives needs to be identified. An MOE addresses stakeholders' requirements and concerns, and measures the degree to which the alternative is able to meet the mission objectives. Two key stakeholder concerns are: survivability of ground platforms and mission success. The MOEs identified to address these concerns are: Percentage of Blue Casualties and Probability of Mission Success. Percentage of Blue Casualties reflects the survivability of ground platforms, and a lower percentage implies higher survivability. The force exchange ratio (FER) was also considered as an MOE; however, it was dropped eventually as FER focuses on attrition warfare, in which the key objective of such warfare is to attrit opponent's strength to a targeted percentage.

B. METHOD OF ANALYSIS

Modeling and simulation (M&S) is used in this study, as it facilitates the analysis of systems' behavior without the need to conduct physical tests. M&S is widely used to model combat scenarios and requires relatively shorter time and lower cost to study the feasibility of alternatives. It allows engineers to understand how systems respond in a virtual environment and identifies areas that need to be improved before physical tests or physical constructions are carried out. M&S also minimizes the effort and cost required to retrofit the physical platform.

C. SIMULATION SOFTWARE SELECTION

The process of determining which software to use starts with analyzing the requirements to obtain the MOEs. To study the effects of sensor properties on ground platform survivability in maneuver operations, a ground force maneuver operations scenario needs to be modeled and simulated. The effects of terrain have to be modeled as terrain affects ground platforms' mobility. Ground platforms, air platforms, and personnel need to be represented in the model as agents with mobility, lethality, sensor capability, and protection characteristics, as well as communication capabilities.

Mobility refers to the agents' movement speed on different types of terrain and during different battlefield situations. Lethality refers to the weapon engagement range, probability of hit and penetration capability, etc. Sensor capability refers to the sensor characteristics, such as detection range, classification range, identification range, etc. Protection refers to level of munition penetration that can be stopped, and the effects on a platform's cover and concealment. Lastly, communication refers to the ability of agents created in the model to exchange information with one another.

The agents created in the model need to have behavioral characteristics to respond to battlefield scenarios, such as engaging, and being engaged by opponents. Most importantly, the software has to generate meaningful data, including force attrition, mission success, time to complete mission, and so forth for analysis.

The software requirements listed can be met using agent-based simulation software. At NPS, Pythagoras Agent-Based Modeling and MANA Agent-Based Modeling software are commonly used. Both are suitable, and MANA was chosen because it offers an online tutorial and research associates with experience in MANA were available at NPS to help the author learn this new software. Sensor attributes such as detection range, average time between detection, sensor classification range and probability, and sensor arc (field of view) can be varied. These features facilitate the study of effects of sensor attributes on a ground platform's survivability during maneuver operations. The next section illustrates the MANA scenario that was created.

D. MANA SCENARIO DESCRIPTION

The scenario is first discussed in Chapter III. The mission is to move Blue ground maneuvering forces, comprising one company of Abrams, Bradleys, and Strykers each from base (right of scenario map) during daytime to a destination (left of scenario map) over a distance of about 20 km. The MANA scenario created is presented in Figure 13. The terrain features modeled in this scenario are light bush, dense bush, water bodies, road, dirt track, and buildings.

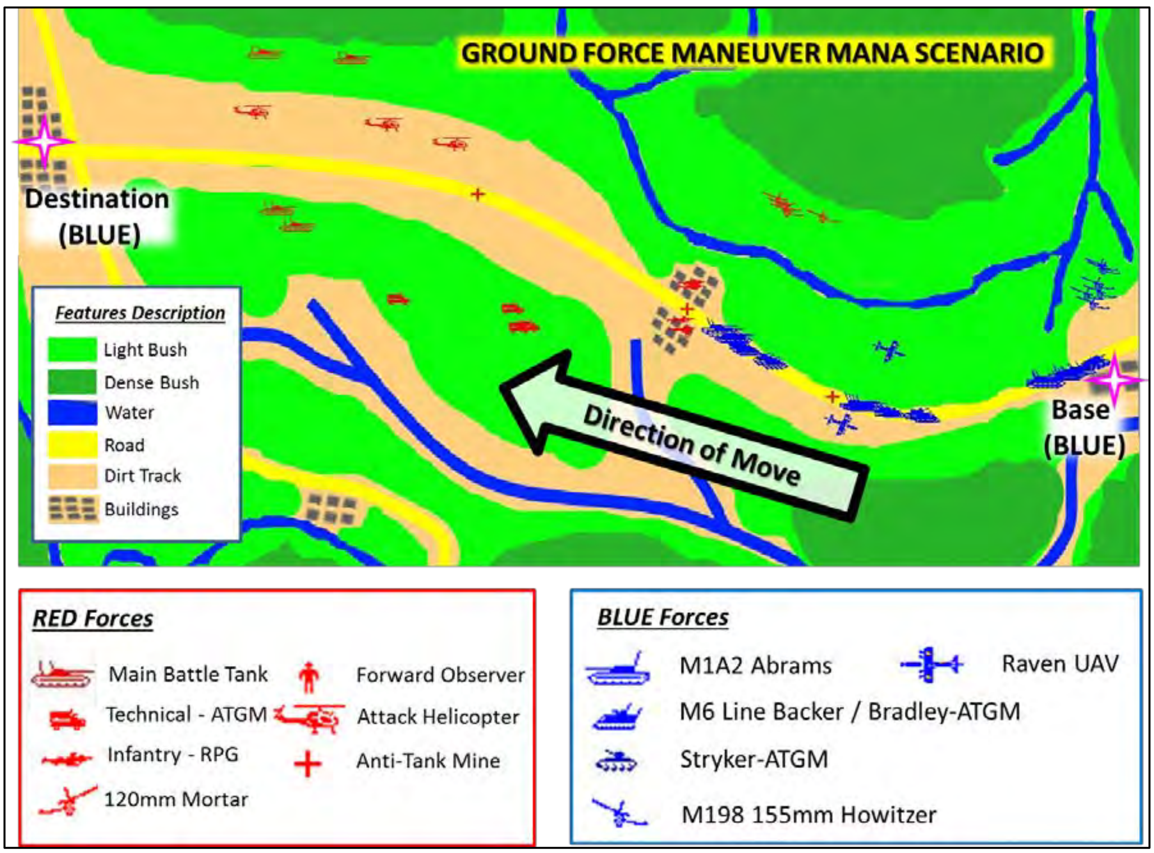

Figure 13. MANA Scenario.

These features each have their own effects on going, cover, and concealment settings, which are tabulated in Table 2. "Going" is a MANA terrain attribute that refers to terrain maneuverability. In MANA, the effects of the three features are represented with a scale of 0 to 1, where 0 means no effect and 1 means full effect. Using "going" as an example, 0 going means the terrain cannot be passed through and 1 means the terrain can be passed through at an agent's maximum speed. Each terrain type is represented by a specific Red Green Blue color code (RGB) setting. Therefore, scenarios can be created in other graphics software and loaded into MANA, and with the corresponding RGB settings entered in the terrain editor, MANA will recognize the terrain and assign it with the correct terrain feature.

Table 2. Terrain Properties.

	Terrain Properties			RGB Setting			
Terrain	Going	Cover	Conceal	Red	Green	Blue	Color
Light bush	0.75	0.1	0.3	10	255	10	Light Green
Dense bush	0.2	0.3	0.9	40	180	40	Dark Green
Water	0	0	0	0	38	255	Blue
Road	1	0	0	255	255	0	Yellow
Dirt Track	0.85	0	0	255	209	127	Brown
Buildings	0	0.5	0.7	96	96	96	Grey

Terrain Elevation is *not* modeled in the MANA scenario, as the hypothetical terrain is generally flat with some vegetation. The author recognizes the reduction in fidelity when terrain elevation is not modeled. The issue arises when ground platforms, given their engagement range, will be able to engage mortar and artillery deployment sites that are typically beyond their line of sight, which is unrealistic. The workaround for not including terrain elevation in the MANA scenario is to not allow Abrams, Bradleys, and Strkyers to engage mortars and artillery. Mortars and artilleries can to engage one another when triggered by Red force forward observer and Blue force UAV respectively.

Agent Evasive Actions are *not* modeled in the MANA scenario as they are TTP that can improve or even reduce the platform's survivability. Not modeling evasive actions might reduce the fidelity of the model. However, TTP are not modeled, as they might influence the results, making it difficult to determine the significance of sensing capabilities on platform survivability. The results obtained from this thesis could be read as the baseline scenario when battle tactics are not incorporated. Instead of incorporating evasive actions for agents to exit the kill zone, the speed of Blue force platforms is reduced by 50 percent to simulate the Blue forces slowing down to locate and destroy the adversaries when being engaged.

Troops seldom fight until total annihilation in reality and would usually retreat or call for reinforcement when attrition reaches a threshold. However, in the model used here, the troops are designed to **fight until total annihilation**. This may seem unrealistic. However, allowing the forces to fight until total annihilation facilitate the study on the effects of the factors to be varied for the simulations.

1. Agent Description and Trigger States

The force structures of Blue and Red forces modeled in the MANA scenario are tabulated in Table 3.

Table 3. Force Structure for Blue and Red Forces.

Blue Force	Size	No. of Agents	Red Force	No. of Agents
M1A2 Abrams MBT	1 Company	12	MBT	4
Bradley-M6 Linebacker IFV	1 Platoon	4	Technical ATGM	4
Bradley-ATGM IFV	2 Platoons	8	Infantry - RPG	4
Strkyer- ATGM IFV	1 Company	12	M120 120mm Mortar	4
Raven UAV	--	2	Forward Observer	1
M198 Howitzer	1 Platoon	6	Attack Helicopter	3
			Anti-Tank Mines	3

The agents' weapon performance and sensing capabilities used in the model follow the settings used in MAJ Tobias Treml's NPS thesis, "An Revolutionary Approach for the Development of Future Ground Combat System Specifications." The weapon systems, sensor systems, and trigger states of Blue and Red agents are provided in Table 4. Trigger states define how agents behave in different situations. Blue force weapon and sensor systems are modeled according to the descriptions in Chapter II. Red force agents are modeled to have capabilities equivalent to those of the Blue forces.

Blue forces are modeled to transit at a constant speed of 56 km/hr or 30 miles/hr (U.S. Army Transportation School 2014). Upon engagement by Red force, Blue forces' speed slows down to half of its traveling speed. The Red forces are modeled to be in 100 percent concealment (ambush in vegetation) during the start of the simulation, and are therefore non-detectable by the UAVs. Their concealment drops to 50 percent when they start firing at the Blue forces, exposing their locations to Blue force sensors.

Table 4. Agent Description.

Agent	Weapon System	Sensor System	Trigger States Used
M1 Abrams (BLUE)	- 120 mm Main Gun - 0.5 CAL Machine Gun (MG) - 7.62mm Coaxial MG - 7.62mm Loader's MG	Thermal Imager (TI) and Electro Optics (EO)	Default State - Movement with weapons and sensors enabled. Enemy Contact State 1 - 50% of movement speed with weapons and sensors enabled when contacted. Run Start - 0% movement speed for 15 minutes after UAV deployed
M6 Linebacker (BLUE)	- 25mm Bushmaster - Stinger Surface to Air Missile - 7.62mm MG	TI and EO	Default State - Movement with weapons and sensors enabled. Enemy Contact State 1 - 50% movement speed with weapons and sensors enabled when contacted. Run Start - 0% movement speed from start until 1 minute after Abrams deployed (movement formation and platform type separation).
Bradley-ATGM (BLUE)	- 25mm Bushmaster - BGM-71 TOW ATGM - 7.62mm MG	TI and EO	Default State - Movement with weapons and sensors enabled. Enemy Contact State 1 - 50% movement speed with weapons and sensors enabled when contacted. Run Start - 0% movement speed from start until 1 minute after Abrams deployed (movement formation and platform type separation). -

Agent	Weapon System	Sensor System	Trigger States Used
Stryker-ATGM (BLUE)	- BGM-71 TOW ATGM - 0.5 CAL MG	TI and EO	Default State - Movement with weapons and sensors enabled. Enemy Contact State 1 - 50% movement speed with weapons and sensors enabled when contacted. Run Start - 0% movement speed from start until 1 minute after Bradleys deployed (movement formation and platform type separation).
Raven UAV (BLUE)	NONE	TI and EO	Default State - Flight Path follows way points with sensors enabled. Enemy Contact - UAV move towards red force when detected.
M198 Howitzer (BLUE)	155 mm artillery munition	NONE	Default State - Weapons enabled and waiting for instructions to engage.
Main Battle Tank (RED)	Same as M1A2 Abrams		Default State - 0% movement in 100% concealment with weapons and sensors enabled. Enemy Contact - 0% movement in 50% concealment with weapons and sensors enabled when contacted.
Technical-ATGM (RED)	- BGM-71 TOW ATGM - 7.62mm MG	TI and EO	Default State - 0% movement in 100% concealment with weapons and sensors enabled. Enemy Contact - Movement towards target in 50% concealment with weapons and sensors enabled when contacted.
INF-RPG (RED)	RPG 7	TI and EO	Default State - 0% movement in 98% concealment with weapons and sensors enabled.

Agent	Weapon System	Sensor System	Trigger States Used
Attack Helicopters (RED)	- Hellfire Missiles - Hydra 70mm Rockets - 30mm Cannon	TI and EO	Default State - Flight Path follows way points with weapons and sensors enabled. Run Start - Launch helicopters 21 minutes to simulate activation of support fire.
120 mm Mortar (RED)	120 mm Mortar munitions	NONE	Default State - Weapons enabled and waiting for instructions to engage.
Forward Observer (RED)	NONE	TI and EO	Default State - 0% movement in 98% concealment with sensors enabled.
Anti-Tank Mine (RED)	Explosive	Pressure Sensor	Default State - 0% movement in 98% concealment with sensors enabled. Taken Shot(Pri) - Agent changes color to indicate activation of mine.

Table 5 presents the Killer Victim Matrix of the agents modeled in MANA. This matrix illustrates the engagement capability of the agents against one another modeled in MANA. Killer represents a shooter agent, and Victim represents the target being shot at. A 'K' denotes the ability of a shooter to kill or destroy a target, and an 'NK' denotes the inability of a shooter to kill or destroy a target. Fratricide does not occur in the MANA model, as agents are modeled to aim and shoot only at opponents.

Table 5. Killer Victim Matrix.

Legend K = Kill NK = No Kill		Victim												
		Blue Forces						Red Forces						
		M1 Abrams	Bradley M6 LineBacker	Bradley-ATGM	Stryker-ATGM	M198 Howitzer	UAV	MBT	Technical-ATGM	INF-RPG	120mm Mortar	Attack Helicopter	Forward Observer	Anti Tank Mines
Killer: Blue Forces	M1 Abrams	No Fracticide						K	K	K	NK	K	K	NK
	Bradley M6 LineBacker							NK	K	K	NK	K	K	NK
	Bradley-ATGM							K	K	K	NK	NK	K	NK
	Stryker-ATGM							K	K	K	NK	NK	K	NK
	M198 Howitzer							K	K	NK	K	NK	NK	NK
	UAV							NK	NK	NK	NK	NK	NK	NK
Killer: Red Forces	MBT	K	K	K	K	NK	K	No Fracticide						
	Technical-ATGM	K	K	K	K	NK	K							
	INF-RPG	K	K	K	K	NK	NK							
	120mm Mortar	K	K	K	K	NK	NK							
	Attack Helicopter	K	K	K	K	NK	K							
	Forward Observer	NK	NK	NK	NK	NK	NK							
	Anti Tank Mines	K	K	K	K	NK	NK							

2. Model Assumptions

Listed are the assumptions for this model:

(1) Fratricide

There is no fratricide, as forces are modeled to shoot only at opponents. Even though it might happen in real situations, the probability of occurrence is probably low as a result of enforcing TTP, such as aim before firing. Including fratricide increases the difficulty in determining the significance of the factors that have effects on platform survivability.

(2) Communication

Communication between Blue forces is 100 percent reliable. This removes the variability in the results due to communication reliability. Moreover, the focus of this analysis is not on communications. Keeping this communication constant allows better study of the effects of sensing capability on platform survivability.

(3) M198 155 mm Howitzer

The Red force is not modeled to be equipped with counter-battery radar systems and UAVs to detect locations where artillery projectiles are fired from. Therefore, the Red force does not have the capability to engage the Blue force M198 Howitzer.

(4) M120 120 mm Mortar

Blue force ground platforms are modeled with the inability to engage the Red force 120 mm mortar platoon even though the platoon is within the Blue force ground platform's detection range. This is to simulate that Blue force ground platforms do not have Line Of Sight to the mortar baseplate position, which is usually true in a real situation. Counter-battery radar systems are not modeled as the additional sensors for Blue force ground platforms as the Blue force UAVs can perform the function of detecting Red force 120 mm mortar platoon.

(5) Environmental Conditions

Effects of weather, such as wind, temperature, and rainfall, cannot be modeled directly in MANA. Changing hit and detection probabilities of agents can be done in MANA to mimic environmental effects. For example, reduction in visibility on rainy days can be modeled by reducing the probability of detection, and effects on trajectory paths of weapons due to wind conditions can be modeled by reducing the probability of hit. However, environment effects may not be uniform within the area of operations, and modeling the effects might give either force an advantage over the other. This increases the difficulty of determining the significance of the factors that have effects on platform survivability. Therefore, the results and analysis are based on a "perfect weather" situation.

(6) Anti-Tank Mines

Blue force ground platforms modeled do not have the capability to detect and destroy anti-tank mines. In addition, platforms with mine plows are also not modeled. However, mines are still included to increase the realism of the scenario. Occurrences of platforms destroyed by mines are based on probability.

(7) Forward Observer

The Red force forward observer's (FO) main task is to spot an incoming Blue force contingent, and activate mortar fire on them. The FO does not carry any weaponry to engage Blue forces.

E. BASELINE MODEL VERIFICATION

The baseline model is comprised of agents that were described in the operational scenario as illustrated in Chapter III. Prior to performing extensive simulation runs with different variable values, there is a need to verify the model created. Two verification tests are conducted to determine whether the agents are behaving in accordance with their behavioral attributes, and they are described in Appendix A. Both tests verify that the model works as designed. The MANA model file and the Excel spreadsheet containing details of agents' settings are being kept with the NPS Seed Center.[1]

F. STOPPING CONDITIONS FOR SIMULATION

The stopping conditions for a single simulation run are the following:

1. Blue force loses all its Ground Platform agents, or
2. When the last Blue force squad reaches the destination, or
3. When the maximum time of 10,000 time steps is reached.

G. DATA ANALYSIS METHODOLOGY

This objective of analyzing alternatives is to find out their effectiveness in improving ground platforms' survivability during maneuver operations. The scope of this thesis studies the effects of sensing capability on ground platform survivability. Through the MANA model created, sensor attributes can be varied to find out their effects on platform survivability. There are many data analysis methods available, and regression analysis and partition tree analysis are assessed to be the most suitable analysis methods to be used for this study.

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[1] Please contact Professor Tom Lucas, Director, Seed Center, twlucas@nps.edu.

1. Regression Analysis

From Chapter XII of Probability and Statistic for Engineers and Scientist, regression analysis is explained as a statistical approach for analyzing relationships between the dependent variable, Y, and one or more independent variables, X. The purpose of this approach is to identify a regression function that can describe the relationship between the variables and to predict the value of the dependent variable when the values of the independent variable changes (Hayter 2012). In this study, the MOEs for platform survivability is the dependent variable, and the sensor attributes are the dependent variables X.

The main effects, two-way interaction and second order polynomial of the variables will be studied to identify the significant variables that affect the platform. The R^2 and adjusted R^2 values obtained from the regression model can be related to the accuracy of predictions made using the regression function derived and depends on how well the regression model fits into the data. R^2, also known as the coefficient of determination (Hayter 2012), is the percentage of variability in responses that can be explained by the regression model, and a high R^2, ideally = 1, is desired.

Residual analysis as explained in Chapter XII of Probability and Statistic for Engineers and Scientist is used to check whether the fitted model is appropriate, the error variance is constant, the error terms are normally distributed, and to identify data points that are outliers (data points that do not follow the general trend of the rest of the data). The analysis is done by examining the residual plot (residual by independent variable plot). Figure 14 depicts the types of residual plots. A random plot means that the data is normally distributed with constant variance, a mean of zero, and that the relationship is linear. It is important to study the residual plot as the regression model is only useful if the following Regression Analysis assumptions are not violated.

1. Residuals are independent
2. Residuals are normally distributed.
3. Residuals have a mean of zero.
4. Residuals have a constant variance.

The last plot on the right of Figure 14 shows a non-linear model (Hayter 2012).

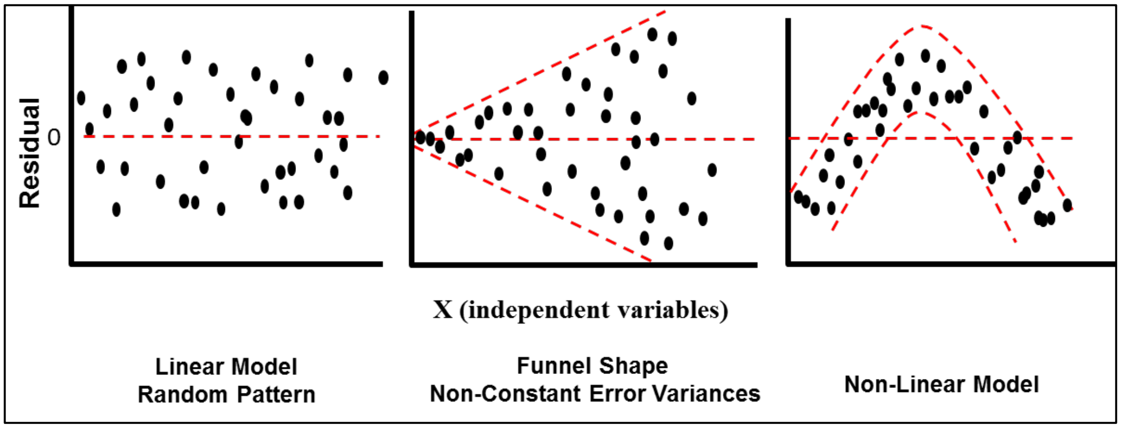

Figure 14. Type of Regression Plots.

2. Partition Tree Analysis

As explained in Chapter XIII of the JMP Manual, "Modeling and Multivariate Methods", unlike regression analysis that requires the residuals to be normally distributed for the model to be useful, partition tree analysis is non-parametric, which means it does not require any distributional assumptions of the data. Partition tree analysis is often used to complement the results of regression. It is a good for exploring relationships between a dependent variable and its independent variables (Cary 2012).

The data set used is recursively partitioned into groups of independent variables X values and identifies the group(s) that best predicts the value of the dependent variable Y, forming a tree-like chart as presented in Figure 15. The creation of the partition tree starts from the top. At the top branch, the most significant dependent variable is identified, and the R^2 based on this variable is also computed. Moving down the tree, the next most significant dependent variable is identified, and when both variables are used to predict the dependent variable, the R^2 value increases. The process of identifying the next significant dependent variable is called splitting. Splitting is performed recursively until the tree cannot be grown further, meaning there are no other significant dependent variables that can be used to predict the value of the dependent variable Y. At this point, the R^2 is the highest. Additional information that the partition tree presents is the threshold value for each significant dependent variable, its mean, standard deviation, and the count of occurrence that is less than, or greater than, and equal to the threshold value.

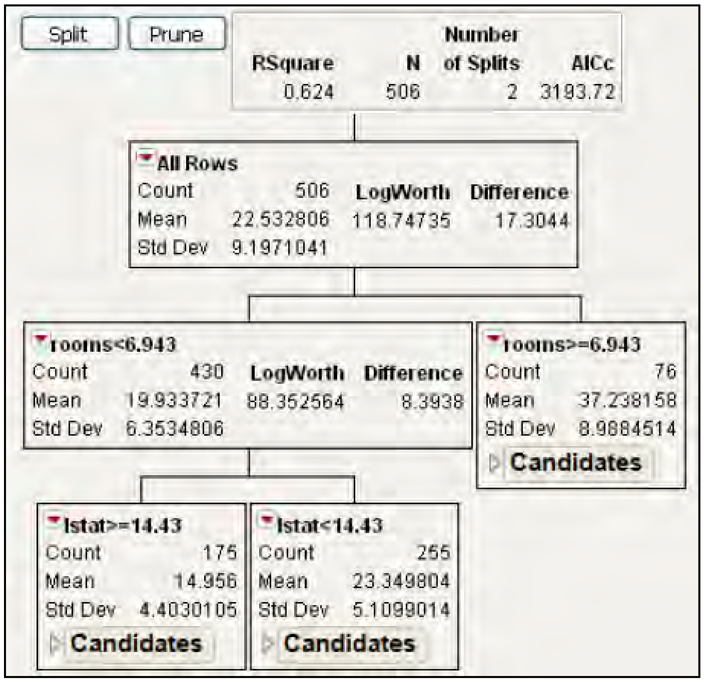

Figure 15. Sample Partition Tree (from Gary NC 2012).

H. SENSOR ATTRIBUTES

The scope of this thesis focuses on the sensing capability of ground platforms' survivability during maneuver operations. Only sensor attributes of Blue forces will be varied, as the focus is on improving Blue forces' survivability. Varying Red forces' sensor attributes adds complexity to the analysis and might dilute the significance of the Blue forces' sensor attributes that are being studied.

1. List of Sensor Attributes

Sensor attributes that seem to affect sensing capability are: (1) Target Detection, (2) Target Classification, (3) Target Identification, (4) Sensor Field of View, and lastly, (5) Speed of UAV. Target Detection is the discovery of a potential target during area scanning. The factors that affect detection are: Range, Probability, and Average Processing Time to Detect. Target Classification is the ability to recognize the type of target that has been detected. The factors that affect classification are: Range, Probability, and Average Processing Time to classify after detection. Target Identification is the ability to determine whether the target classified is a friend or a foe. The factors that affect identification are: Probability and Average Processing Time to identify after classification. Sensor Field of View is the angular area that can be seen within the observable angle of the sensor at any given time.

The listed attributes can be varied in the MANA software except for target identification, detection probability, and average processing time to classify because features to vary these three attributes are not available in MANA. Each type of Blue platform has its own unique sensor attributes. The sensing capability for Bradley-ATGM and M6 Linebackers is assumed to be the same for ease of fleet configuration management since the baseline platform for both are Bradley IFV. Table 6 presents the list of 22 factors that can be varied to study the effects of sensing capability on platform survivability. The factors studied are the attributes of the lower level functions of the Maneuver Ground Force function as described in Table 1. Mapping these factors to their respective functions, and presenting them in Table 6, provides traceability of the factors chosen. This facilitates the verification of the relationship between the factors and the functions of ground force maneuver operations.

Table 6. List of Factors Available for Sensing Effects Study.

Attribute	Function	Platform	Factors that can be varied	
Target Detection	2.1 Detect Objects	Raven UAV	Range	Average Processing time to detect
		M1A2 Abrams	Range	Average Processing time to detect
		Bradley	Range	Average Processing time to detect
		Stryker-ATGM	Range	Average Processing time to detect
Target Classification	2.2 Classify Objects	Raven UAV	Range	Probability
		M1A2 Abrams	Range	Probability
		Bradley	Range	Probability
		Stryker-ATGM	Range	Probability
Sensor Field of View (FOV)	2.1 Detect Objects	Raven UAV	FOV Angle	
		M1A2 Abrams	FOV Angle	
		Bradley	FOV Angle	
		Stryker-ATGM	FOV Angle	
UAV Speed	1.1.Navigate Route	Raven UAV	Speed	
Total number of factors			**22**	

2. Sensor Attributes Studied

For agents to engage an opponent, they must be able to classify their opponent before they can fire on it. The detection range and classification of sighting systems are designed to match, if not exceed, the weapons systems engagement range. This implies that even when the agent is able to "see" its opponent, the agent would not be able to engage if the opponent agent is out of its weapon engagement range. It is noted that having the ability to "see" its opponent beyond its engagement range allows an agent to take evasive actions or use other battle tactics to avoid or destroy its opponent. Since the focus of this study is not on battle tactics but on technology, the following factors will be studied to analyze their effects on ground platform survivability during maneuver operations:

1. Probability of classification at maximum classification range (Range: 0.5 to 0.85)

   The probability of classification determines probability of classification at every scan. High probability means a higher chance of classification at first scan, which implies shorter classification time.

2. UAV's speed (Range: 31 km/hr to 81 km/hr (AeroVironment 2014))

   How fast the UAV can return to the previous scanned area affects the effectiveness of the aerial surveillance. Red forces might appear after the UAV flies out of its sensor detection zone to engaged Blue forces. When this happens, artillery support cannot be activated, and ground platforms might not be able to see Red forces that are not within their line of sight.

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V. DESIGN OF EXPERIMENTS

A well-designed experiment allows the analyst to examine many more factors than would otherwise be possible, while providing insights that could not be gleaned from trial-and-error approaches or by sampling factors one at a time. (Sanchez, 2005).

The objective of Design of Experiment (DOE) is to maximize the amount of information from a given number of simulation runs that can help the analyst understand the system modeled. It is a systematic approach to gather meaning from data points of the system's performance by varying the values of a set of independent variables (factors) which have effects on performance. A good DOE identifies a set of simulation runs that helps the analyst learn about the model in an efficient manner, without missing any important combinations or design points or wasting resources by simulating redundant runs. The number of simulation runs depends on the number factors and the DOE methodologies used. While there are various DOE methodologies that can be used, the nearly orthogonal Latin hypercube (NOLH) is used in this thesis.

A. NEARLY ORTHOGONAL LATIN HYPERCUBE

NOLH is a statistical method that has good space-filling properties of a factorial design even though it uses a lesser number of design points to study the effects of factors on system performance. Good space-filling designs have design points spread throughout the entire design region with minimal unsampled spaces within the region.

Susan Sanchez, from the Operations Research (OR) Department at NPS, explains the difference between factorial design and Latin Hypercube in a very concise and easy-to-understand manner in her paper. Figure 16 depicts the difference between factorial design and Latin Hypercube sampling. Using the factorial approach, two factors each with two levels (the low and high extreme values) will result in four design points (2^2). When the number of levels increases to 11, there will be 121 design points (11^2). Using the Latin Hypercube sampling approach, 11 design points would be adequate for an analyst to study the effects of the factors on system's performance (Sanchez 2005).

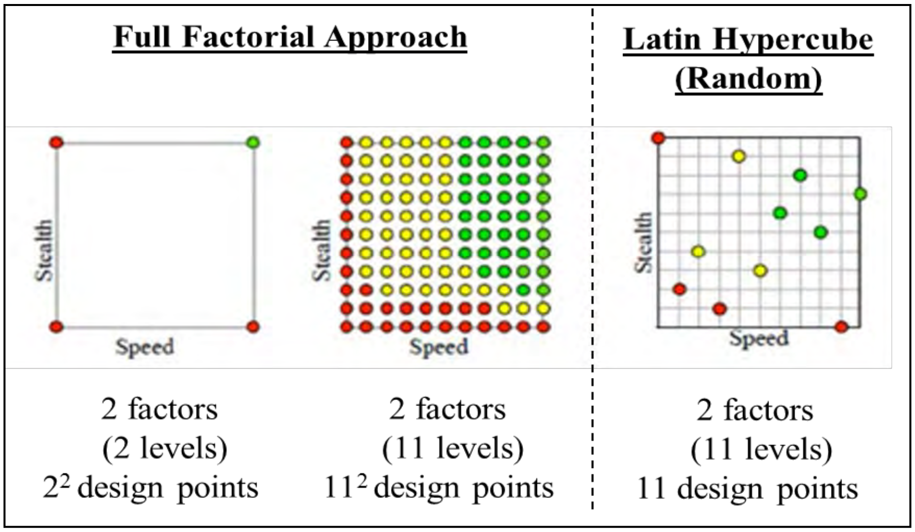


Figure 16. Comparison between Full Factorial Approach and Latin Hypercube (from Sanchez 2005).

Latin Hypercube designs have a good orthogonality. Orthogonality means the design points are independent, and the results of one design point will not be dependent on the other design points. Orthogonality is determined by comparing the pairwise correlation value of two factors, and the correlation values are between -1 to 1. A “0” means no correlation between the two factors, and a “+/- 1” implies perfect linear correlation. It is desirable for the correlation value between factors to be as close to “0” as possible to achieve orthogonality. The guideline to determine orthogonality is correlation value less than +/-0.03 (Cioppa and Lucas, 2007). Furthermore, according to the author’s discussion with Professor Thomas W. Lucas of the OR Department at NPS, +/- 0.05 is also acceptable. The independence of each design point facilitates the discovery of the effects that each factor has on a system’s performance.

Latin Hypercube design generates a set of design points at random. One common approach when Latin Hypercube design is used is to generate multiple Latin Hypercube designs and identify a good one for further analysis. Thomas M. Cioppa, from the U.S. Army Training and Doctrine Command Analysis Center, and Lucas, from the OR department in NPS, developed the NOLH designs used in this study in Microsoft Excel.

This NOLHdesigns.xls excel spreadsheet[2] allows the analyst to specify the factors, and the low and high levels of each factor, which immediately outputs a set of NOLH designs that have good space-filling and orthogonality properties. The spreadsheet contains five different worksheets, and each worksheet generates a specific number of design points for specific ranges of number of factors. Table 7 presents the details of the five types of NOLH designs available.

Table 7. Available NOLH Designs.

No. of design factors	No. of design points generated
2 to 7	17
8 to 11	33
12 to 16	65
17 to 22	129
23 to 29	257

When more design points are used, the orthogonality of the set of NOLH designs improves. Increasing the number of design points is a good technique to improve the orthogonality when the input factors have relatively small ranges of low and high levels. Such factors typically have higher pairwise correlation, resulting in less orthogonality.

B. DESIGN POINTS GENERATED FOR SIMULATION

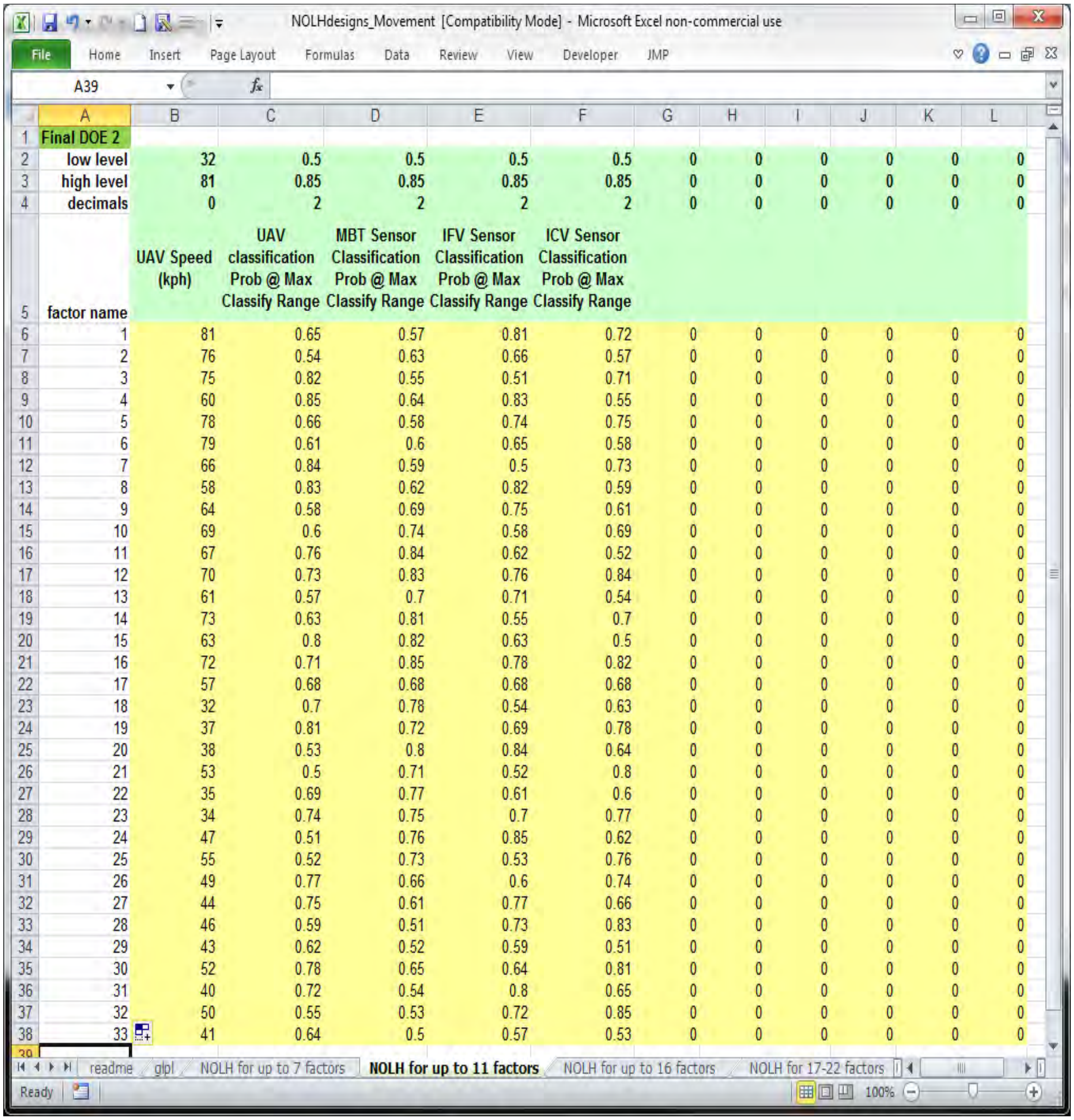
The factors studied in this thesis are the UAV speed and sensor classification probability at maximum classification range for the UAV, Abrams MBT, Bradley IIFVs, and Stryker ICVs. The range of values to be varied for the five factors is presented in Table 8.

[2] The NOLHdesigns.xls Excel spreadsheet can be downloaded from the NPS Seed Center's data farming website at http://harvest.nps.edu/,

Table 8. Design Factor Details.

Design Factor	Low Value	High Value	Remarks
UAV speed	32 kph	81 kph	According to Raven operating speed range (AeroVironment 2014).
UAV sensor classification probability at maximum classification range	0.5	0.85	It is assumed that at maximum classification range, the probability of classification ranges between 0.5 and 0.85, as the highest probability of classification is usually not at the maximum range.
Abrams MBT sensor classification probability at maximum classification range	0.5	0.85	
Bradley IFV sensor classification probability at maximum classification range	0.5	0.85	
Stryker ICV sensor classification probability at maximum classification range	0.5	0.85	

The set of design points generated using version 6 of the NOLH spreadsheet (Sanchez 2011) is presented in Figure 17. Although only five factors are being studied, the 8-to-11 factors NOLH worksheet that generates 33 design points was used. There is no need to intentionally increase the number of factors from five to eight, or to 11. Five factors still work perfectly well when the 8-to-11 factors NOLH worksheet is used. Those columns that are not used can be left blank as each column is independent of the others.



	A	B	C	D	E	F	G	H	I	J	K	L
1	Final DOE 2											
2	low level	32	0.5	0.5	0.5	0.5	0	0	0	0	0	0
3	high level	81	0.85	0.85	0.85	0.85	0	0	0	0	0	0
4	decimals	0	2	2	2	2	0	0	0	0	0	0
5	factor name	UAV Speed (kph)	UAV classification Prob @ Max Classify Range	MBT Sensor Classification Prob @ Max Classify Range	IFV Sensor Classification Prob @ Max Classify Range	ICV Sensor Classification Prob @ Max Classify Range						
6	1	81	0.65	0.57	0.81	0.72	0	0	0	0	0	0
7	2	76	0.54	0.63	0.66	0.57	0	0	0	0	0	0
8	3	75	0.82	0.55	0.51	0.71	0	0	0	0	0	0
9	4	60	0.85	0.64	0.83	0.55	0	0	0	0	0	0
10	5	78	0.66	0.58	0.74	0.75	0	0	0	0	0	0
11	6	79	0.61	0.6	0.65	0.58	0	0	0	0	0	0
12	7	66	0.84	0.59	0.5	0.73	0	0	0	0	0	0
13	8	58	0.83	0.62	0.82	0.59	0	0	0	0	0	0
14	9	64	0.58	0.69	0.75	0.61	0	0	0	0	0	0
15	10	69	0.6	0.74	0.58	0.69	0	0	0	0	0	0
16	11	67	0.76	0.84	0.62	0.52	0	0	0	0	0	0
17	12	70	0.73	0.83	0.76	0.84	0	0	0	0	0	0
18	13	61	0.57	0.7	0.71	0.54	0	0	0	0	0	0
19	14	73	0.63	0.81	0.55	0.7	0	0	0	0	0	0
20	15	63	0.8	0.82	0.63	0.5	0	0	0	0	0	0
21	16	72	0.71	0.85	0.78	0.82	0	0	0	0	0	0
22	17	57	0.68	0.68	0.68	0.68	0	0	0	0	0	0
23	18	32	0.7	0.78	0.54	0.63	0	0	0	0	0	0
24	19	37	0.81	0.72	0.69	0.78	0	0	0	0	0	0
25	20	38	0.53	0.8	0.84	0.64	0	0	0	0	0	0
26	21	53	0.5	0.71	0.52	0.8	0	0	0	0	0	0
27	22	35	0.69	0.77	0.61	0.6	0	0	0	0	0	0
28	23	34	0.74	0.75	0.7	0.77	0	0	0	0	0	0
29	24	47	0.51	0.76	0.85	0.62	0	0	0	0	0	0
30	25	55	0.52	0.73	0.53	0.76	0	0	0	0	0	0
31	26	49	0.77	0.66	0.6	0.74	0	0	0	0	0	0
32	27	44	0.75	0.61	0.77	0.66	0	0	0	0	0	0
33	28	46	0.59	0.51	0.73	0.83	0	0	0	0	0	0
34	29	43	0.62	0.52	0.59	0.51	0	0	0	0	0	0
35	30	52	0.78	0.65	0.64	0.81	0	0	0	0	0	0
36	31	40	0.72	0.54	0.8	0.65	0	0	0	0	0	0
37	32	50	0.55	0.53	0.72	0.85	0	0	0	0	0	0
38	33	41	0.64	0.5	0.57	0.53	0	0	0	0	0	0

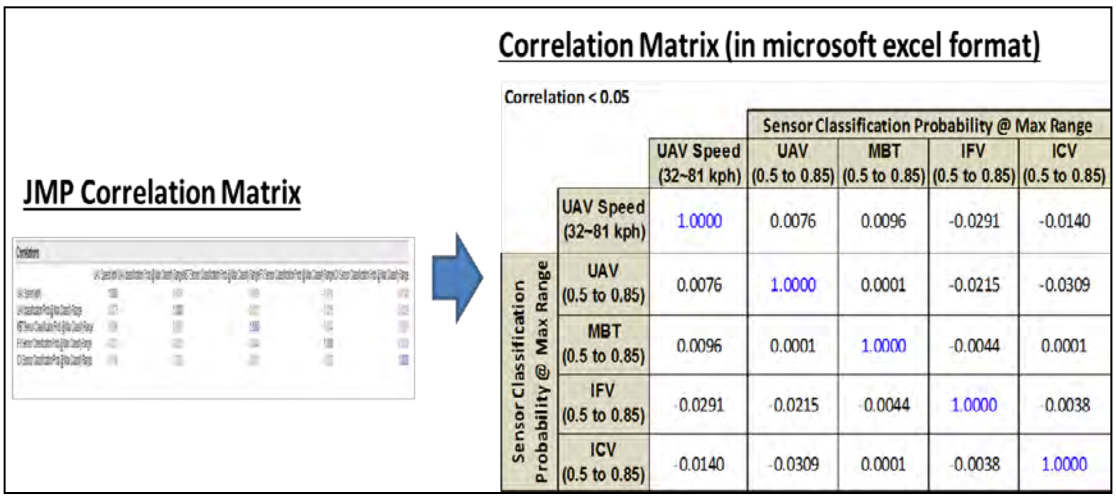
Figure 17. NOLH Design for Ground Force Maneuver Operation Analysis.

The set of design points is analyzed using JMP PRO V10 (JMP) software to verify that the space-filling properties and orthogonality are within acceptable threshold levels before the simulation runs are carried. Figure 18 and Figure 19 present the two-dimensional Correlation Matrix and Scatter Plot Matrix generated in JMP. The Correlation Matrix was recreated in Microsoft Excel as the JMP-generated Correlation Matrix is not so readable.

The correlation values presented in the Correlation Matrix are known as Pearson Correlation Coefficients (Corr), which are computed using the following equation (Hayter 2012).

Corr (X,Y) = Pearson Correlation and Cov(X,Y) = Covariance of XY, where X and Y represents the two factors that are being compared.

The Correlation Matrix presents the results of the pairwise correlation of all five factors, and all the correlation values are within the +/- 0.05 guideline. From the Scatter Plot Matrix, there is also no large empty region observed.



		UAV Speed (32~81 kph)	Sensor Classification Probability @ Max Range UAV (0.5 to 0.85)	MBT (0.5 to 0.85)	IFV (0.5 to 0.85)	ICV (0.5 to 0.85)
	UAV Speed (32~81 kph)	1.0000	0.0076	0.0096	-0.0291	-0.0140
Sensor Classification Probability @ Max Range	UAV (0.5 to 0.85)	0.0076	1.0000	0.0001	-0.0215	-0.0309
	MBT (0.5 to 0.85)	0.0096	0.0001	1.0000	-0.0044	0.0001
	IFV (0.5 to 0.85)	-0.0291	-0.0215	-0.0044	1.0000	-0.0038
	ICV (0.5 to 0.85)	-0.0140	-0.0309	0.0001	-0.0038	1.0000

Figure 18. Factors Correlation Matrix.

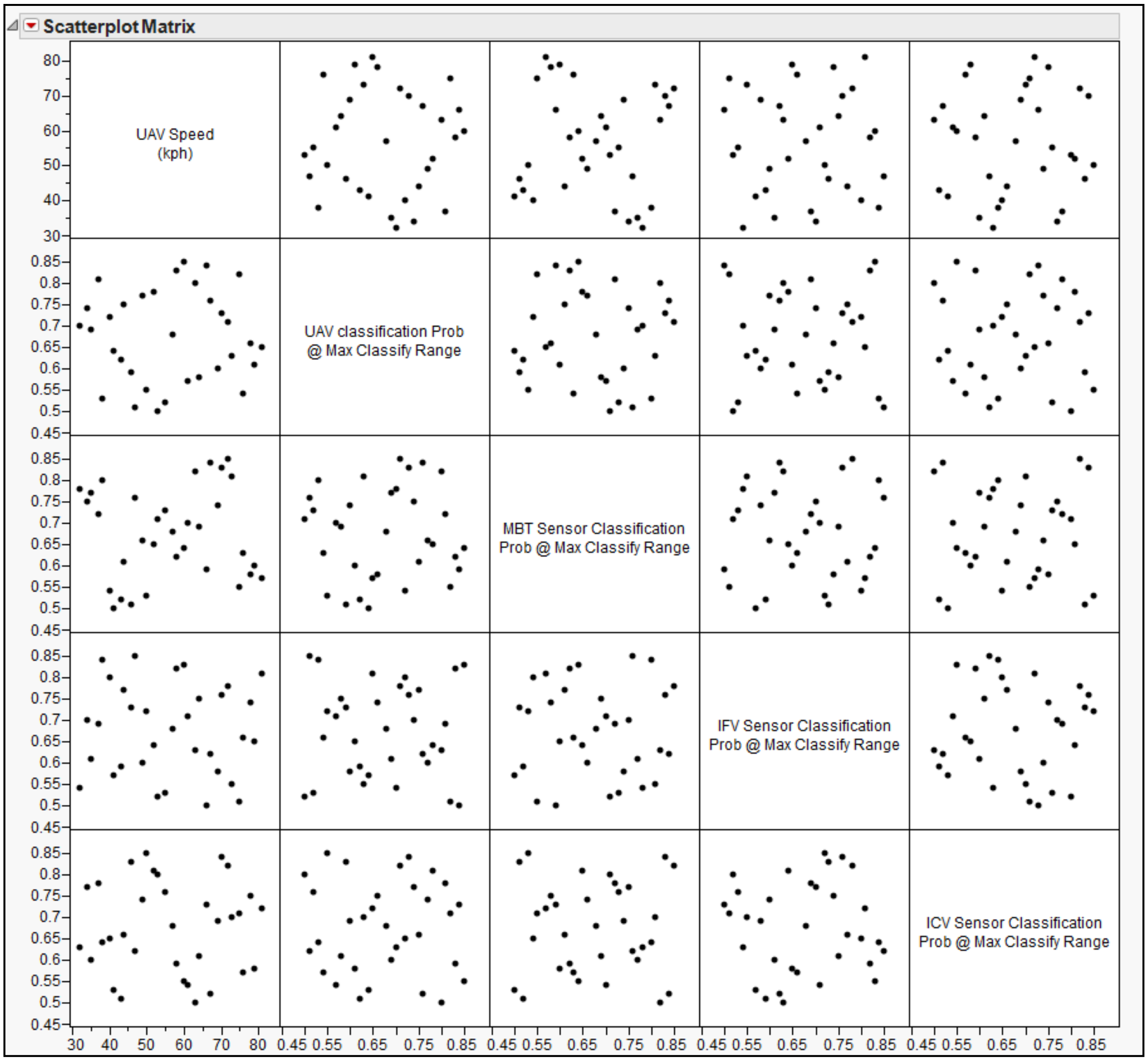


Figure 19. Scatter Plot Matrix.

Outcomes from the Correlation Matrix and Scatter Plot Matrix verify that the set of NOLH-created design points has achieved good space-filling properties and orthogonality. With the set of design points determined, the next step is to perform simulation runs and gather results for further analysis.

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VI. RESULTS

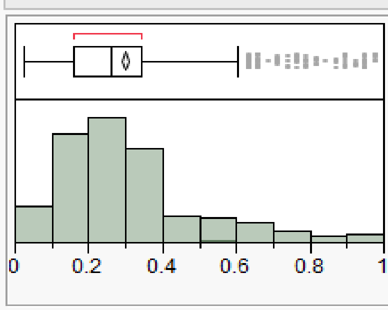
This chapter presents the results obtained from simulation runs of 33 design points. Each design point simulation was repeated for 50 replications, and a total of 1650 data points were collected and analyzed. Details of the full results can be found in Appendix A. The number of Blue casualties, probability of mission success, and time to complete mission are the three MANA-generated results being measured.

The results for number of Blue casualties were further processed to obtain the percentage of Blue casualties. Variability in the results indicates that the factors (UAV Speed and Sensor Classification Probability at maximum classification range of various platforms) have effects on the survivability of the ground maneuver forces.

A. PERCENTAGE OF BLUE CASUALTIES

Variability can be observed from the distribution plots for percentage of Blue casualties. The percentage of Blue casualties observed vary from 2.6 to 97.4 percent, which indicates that the factors do have an effect. See Figure 20.

Blue Cas %



Quantiles

100.0%	maximum	0.97368
99.5%		0.94737
97.5%		0.83487
90.0%		0.57895
75.0%	quartile	0.34211
50.0%	median	0.26316
25.0%	quartile	0.15789
10.0%		0.10526
2.5%		0.05263
0.5%		0.02632
0.0%	minimum	0.02632

Summary Statistics

Mean	0.2993142
Std Dev	0.1877706
Std Err Mean	0.0046226
Upper 95% Mean	0.308381
Lower 95% Mean	0.2902474
N	1650

Figure 20. Percentage Blue Casualties.

B. PROBABILITY OF MISSION SUCCESS

For a fight-to-the-finish simulation, mission success is achieved when the last Blue agent reaches the destination, regardless of the number of Blue forces remaining. It is observed that the mean probability of mission success for the 1,650 simulation is close to 0.979, and there is little variability in the results. It is also observed that the Red forces are totally annihilated for most of the runs, which explains the high probability of mission success.

However, it is not realistic for a ground maneuver force to fight until the last platform. A retreat would most likely be initiated after suffering an attrition of more than 50 percent (hypothetical percentage). Therefore, the data collected was further processed to consider mission success, if the remaining force size upon reaching the destination is more than 50 percent. The mean mission success rate decreases to about 87.2 percent. However, again not much variability is observed. Therefore, this implies that the factors studied do not have any significant effect on the probability of mission success.

C. TIME TO COMPLETE MISSION

Results for the time to complete mission (fight-to-the-finish) is presented in Figure 21. For the distribution plot, little variation is observed, and the mean mission completion time is about 4,016 seconds (~1.2 hours). The minimal variation implies that the factors have no significant effect on the time to complete mission.

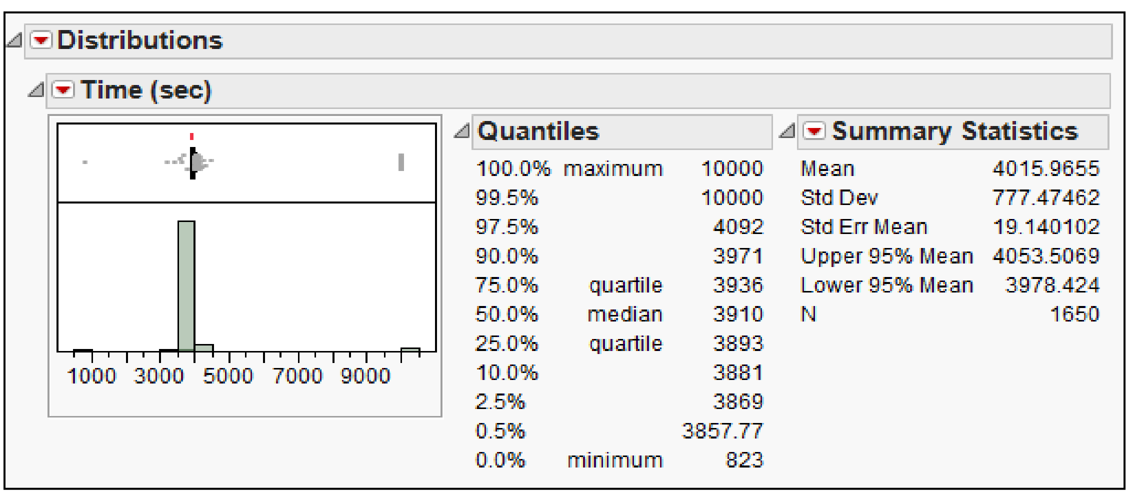


Figure 21. Time to Complete Mission.

The results will be further analyzed in the next chapter to identify the significant factors that affect platform survivability.

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VII. DATA ANALYSIS

Two types of data analysis will be presented in this chapter: regression analysis and partition tree analysis. These two analyses identify the significant factors that affect the percentage of Blue casualties, which reflects the survivability of the ground maneuver force. The mean of percentage of Blue casualties from 50 replications, each of the 33 simulation design points, are used for both analyses.

A. REGRESSION ANALYSIS

Residual analysis is first performed to determine the usefulness of the regression model. The Residual by Predicted plot shows randomness, indicating that the four assumptions for regression analysis (as described in Section G.1) are not violated, and that the regression model is a useful model. See Figure 22.

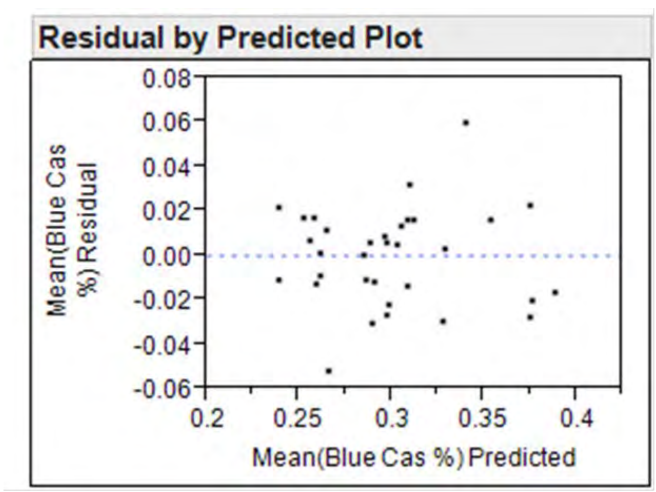
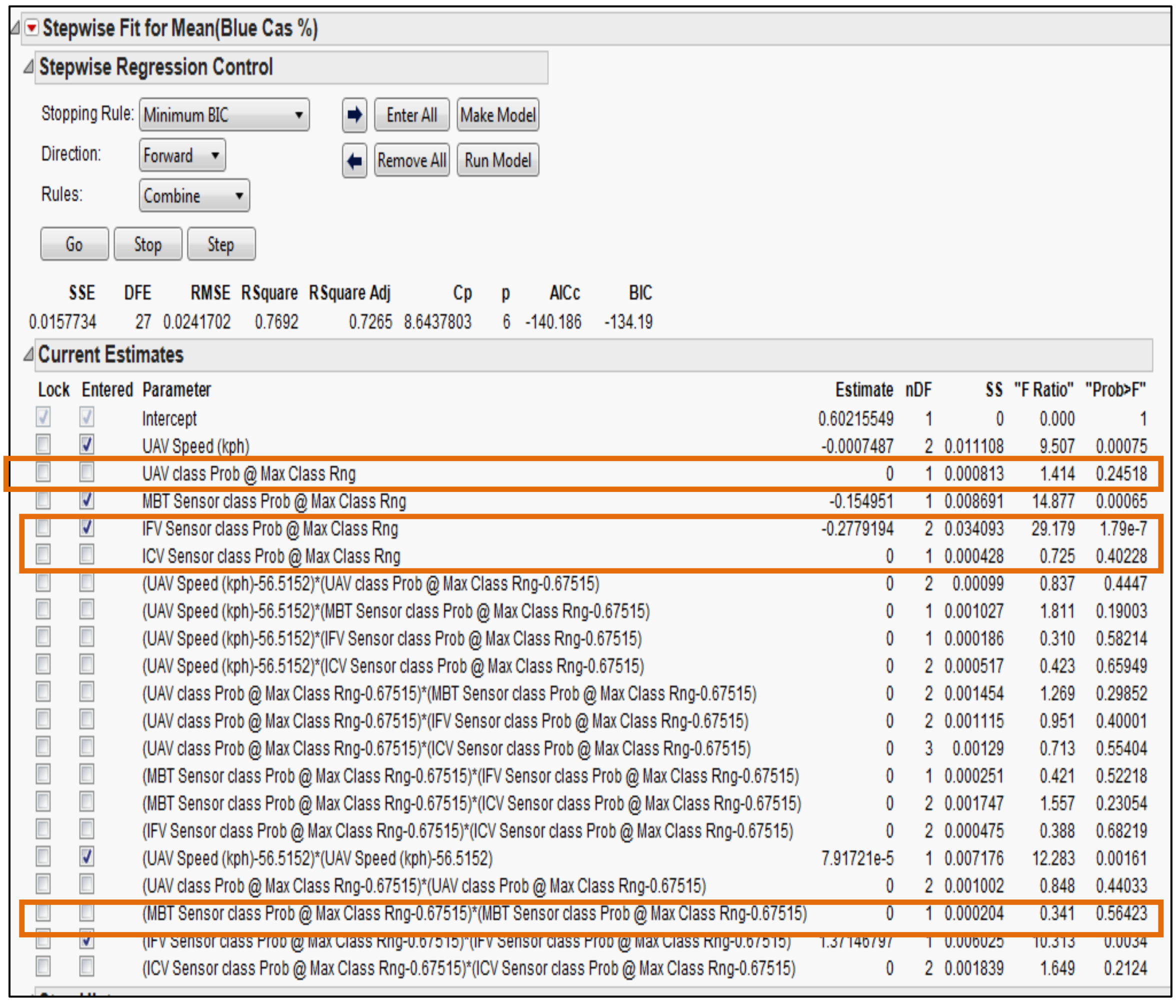


Figure 22. Residual by Predicted Plot.

The main effects, two-way interactions, and second order polynomials of the factors are being analyzed for the regression model. The stepwise regression analysis performed is shown in Figure 23. This analysis is a function in JMP that automatically identifies the significant terms (main effects, two-way interactions, and second order polynomials) and omits the rest that are insignificant to the percentage of Blue casualties to develop the regression model. Five terms have been identified to have significant effects on percentage of Blue casualty: (1) IFV sensor classification probability, (2) MBT sensor classification probability, (3) UAV Speed * UAV speed, (4) IFV sensor classification probability * IFV sensor classification probability, and (5) UAV speed. Classification probability refers to the probability at the sensors maximum classification range. The five terms have p-values less than 0.05, and factors that have p-values less than 0.05 are classified as significant factors. When p-values of factors are low, the null hypotheses that the factors do not have any significance are rejected.



SSE	DFE	RMSE	RSquare	RSquare Adj	Cp	p	AICc	BIC
0.0157734	27	0.0241702	0.7692	0.7265	8.6437803	6	-140.186	-134.19

Lock	Entered	Parameter	Estimate	nDF	SS	"F Ratio"	"Prob>F"
✓	✓	Intercept	0.60215549	1	0	0.000	1
	✓	UAV Speed (kph)	-0.0007487	2	0.011108	9.507	0.00075
		UAV class Prob @ Max Class Rng	0	1	0.000813	1.414	0.24518
	✓	MBT Sensor class Prob @ Max Class Rng	-0.154951	1	0.008691	14.877	0.00065
	✓	IFV Sensor class Prob @ Max Class Rng	-0.2779194	2	0.034093	29.179	1.79e-7
		ICV Sensor class Prob @ Max Class Rng	0	1	0.000428	0.725	0.40228
		(UAV Speed (kph)-56.5152)*(UAV class Prob @ Max Class Rng-0.67515)	0	2	0.00099	0.837	0.4447
		(UAV Speed (kph)-56.5152)*(MBT Sensor class Prob @ Max Class Rng-0.67515)	0	1	0.001027	1.811	0.19003
		(UAV Speed (kph)-56.5152)*(IFV Sensor class Prob @ Max Class Rng-0.67515)	0	1	0.000186	0.310	0.58214
		(UAV Speed (kph)-56.5152)*(ICV Sensor class Prob @ Max Class Rng-0.67515)	0	2	0.000517	0.423	0.65949
		(UAV class Prob @ Max Class Rng-0.67515)*(MBT Sensor class Prob @ Max Class Rng-0.67515)	0	2	0.001454	1.269	0.29852
		(UAV class Prob @ Max Class Rng-0.67515)*(IFV Sensor class Prob @ Max Class Rng-0.67515)	0	2	0.001115	0.951	0.40001
		(UAV class Prob @ Max Class Rng-0.67515)*(ICV Sensor class Prob @ Max Class Rng-0.67515)	0	3	0.00129	0.713	0.55404
		(MBT Sensor class Prob @ Max Class Rng-0.67515)*(IFV Sensor class Prob @ Max Class Rng-0.67515)	0	1	0.000251	0.421	0.52218
		(MBT Sensor class Prob @ Max Class Rng-0.67515)*(ICV Sensor class Prob @ Max Class Rng-0.67515)	0	2	0.001747	1.557	0.23054
		(IFV Sensor class Prob @ Max Class Rng-0.67515)*(ICV Sensor class Prob @ Max Class Rng-0.67515)	0	2	0.000475	0.388	0.68219
	✓	(UAV Speed (kph)-56.5152)*(UAV Speed (kph)-56.5152)	7.91721e-5	1	0.007176	12.283	0.00161
		(UAV class Prob @ Max Class Rng-0.67515)*(UAV class Prob @ Max Class Rng-0.67515)	0	2	0.001002	0.848	0.44033
		(MBT Sensor class Prob @ Max Class Rng-0.67515)*(MBT Sensor class Prob @ Max Class Rng-0.67515)	0	1	0.000204	0.341	0.56423
	✓	(IFV Sensor class Prob @ Max Class Rng-0.67515)*(IFV Sensor class Prob @ Max Class Rng-0.67515)	1.37146797	1	0.006025	10.313	0.0034
		(ICV Sensor class Prob @ Max Class Rng-0.67515)*(ICV Sensor class Prob @ Max Class Rng-0.67515)	0	2	0.001839	1.649	0.2124

Figure 23. Stepwise Regression Analysis.

The five terms are subsequently used to create the regression model, and Figure 24 presents the Actual by Predict plot. The Actual by Predicted plot shows how well the regression model fits the actual data collected. The solid line represents the regression model, and the dots represent the data, mean percentage of Blue casualties, collected from the simulation runs. The better the dots fit to the regression model, the better the regression model is able to explain the variation in percentage of Blue casualties. It is observed that most of the data fell within the two boundaries. The R^2 of this regression model is 0.769, implying that about 76.9 percent of the variation in responses (percentage Blue casualties) can be explained by this regression model.

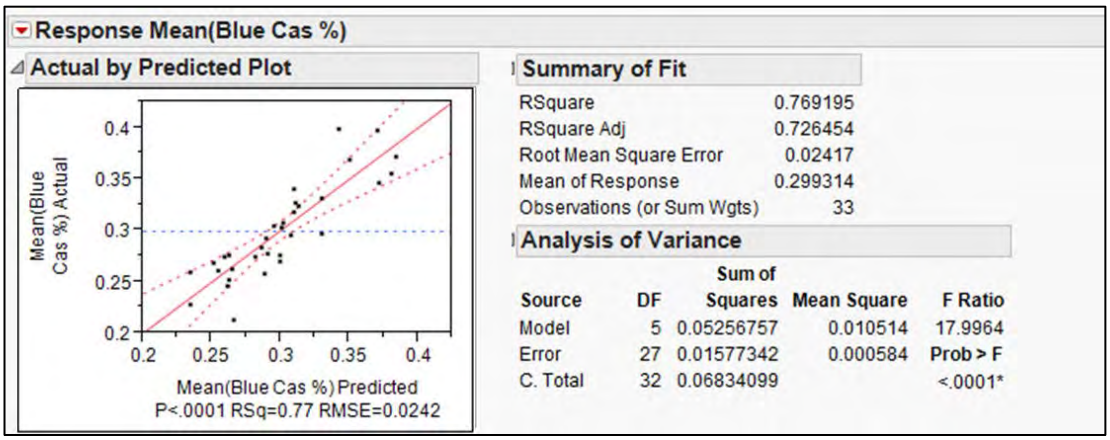


Figure 24. Actual by Predicted Plot for Regression Model.

The effects analysis presented in Figure 25 presents the five significant terms of the regression model, in order of significance: (1) IFV sensor classification probability, (2) MBT sensor classification probability, (3) UAV Speed * UAV Speed, (4) IFV sensor classification probability * IFV sensor classification probability, (5) UAV speed.

The Pareto chart on the right of Figure 25 shows that increasing IFV sensor classification probability has the greatest effect on percentage of Blue casualty reduction. This could be due to the ability of the Bradley M6-Linebacker to destroy Red force attack helicopters more effectively, as attack helicopters are effective in destroying ground platforms. However, its second order polynomial term shows that the increase in probability would increase the casualty percentage to only a smaller extent. This characteristic is also represented in the prediction profiler plot for mean percentage of Blue casualties against IFV sensor classification probability. It is observed that when IFV sensor classification increases to beyond approximately 0.78, the percentage of Blue casualties starts to increase.

MBT sensor classification probability has the next highest effect in reducing the percentage of Blue casualties, and increasing sensor classification probability increases the MBT's lethality, enabling the platform to kill more adversaries.

UAV speed has the least effect in reducing the percentage of Blue casualties among the five terms identified. The second order polynomial term of UAV speed shows that increased speed causes the percentage of Blue casualties to increase. One possible reason could be due to the shorter duration to process the video transferred from the UAV to headquarters, and that might have resulted in the target to miss being detected. From the prediction profile plot for UAV speed, the maximum speed that gives the lowest Blue casualty percentage is approximately 60 km/hr. At higher speeds, the percentage of Blue casualties increases.

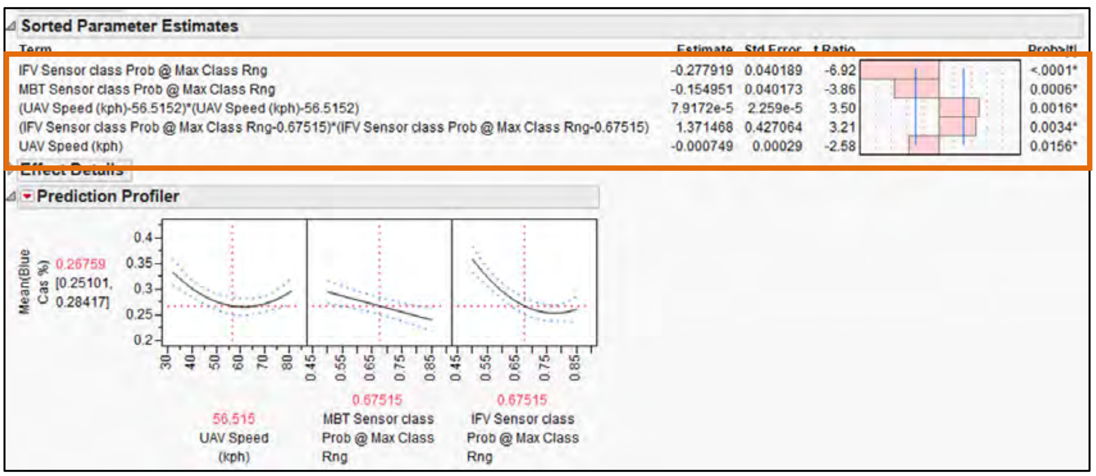
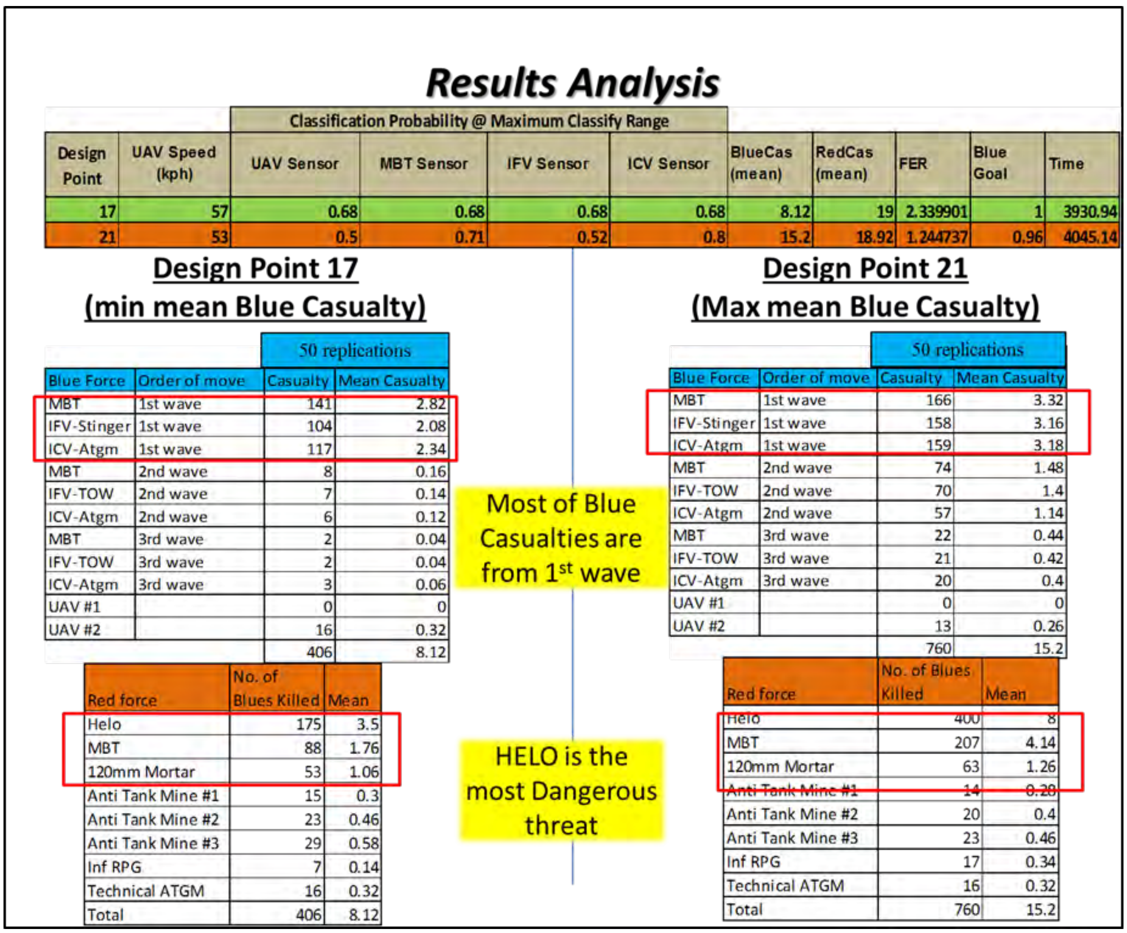


Figure 25. Effects Analysis and Prediction Profiler.

An analysis of the simulation results of design point 17 (least percentage of Blue casualties) and design point 21 (highest percentage of Blue casualties) is shown in Figure 26. The analysis on the Blue casualties profile for both design points revealed that most of the Blue force casualties are suffered by the first team of the ground maneuver force. The mean number of Blue casualties for the first team ranges from two to three for each of the three types of platforms, indicating more than 50 percent of the first team is killed by the Red forces. From the Red force killing profile, the attack helicopters are the most dangerous threat, as they kill the highest number of Blue agents. The high rate of Blue casualties in the first team is due to successful engagements by the Red attack helicopters.

The regression model identifies that the IFV sensor classification probability of as the most significant factor. The Bradley-M6 Linebacker has the air defense capability to destroy attack helicopters. A higher sensor classification probability for the M6 Linebackers means a higher chance of destroying the adversary attack helicopters first. By eliminating the main threat, the number of Blue casualties would be reduced. This illustrates the importance of having air defense assets for ground maneuver forces as ground platforms are highly vulnerable to air attacks, more so when there is no information on adversary force structure.



		Classification Probability @ Maximum Classify Range								
Design Point	UAV Speed (kph)	UAV Sensor	MBT Sensor	IFV Sensor	ICV Sensor	BlueCas (mean)	RedCas (mean)	FER	Blue Goal	Time
17	57	0.68	0.68	0.68	0.68	8.12	19	2.339901	1	3930.94
21	53	0.5	0.71	0.52	0.8	15.2	18.92	1.244737	0.96	4045.14

Design Point 17 (min mean Blue Casualty)

		50 replications	
Blue Force	Order of move	Casualty	Mean Casualty
MBT	1st wave	141	2.82
IFV-Stinger	1st wave	104	2.08
ICV-Atgm	1st wave	117	2.34
MBT	2nd wave	8	0.16
IFV-TOW	2nd wave	7	0.14
ICV-Atgm	2nd wave	6	0.12
MBT	3rd wave	2	0.04
IFV-TOW	3rd wave	2	0.04
ICV-Atgm	3rd wave	3	0.06
UAV #1		0	0
UAV #2		16	0.32
		406	8.12

Red force	No. of Blues Killed	Mean
Helo	175	3.5
MBT	88	1.76
120mm Mortar	53	1.06
Anti Tank Mine #1	15	0.3
Anti Tank Mine #2	23	0.46
Anti Tank Mine #3	29	0.58
Inf RPG	7	0.14
Technical ATGM	16	0.32
Total	406	8.12

Design Point 21 (Max mean Blue Casualty)

		50 replications	
Blue Force	Order of move	Casualty	Mean Casualty
MBT	1st wave	166	3.32
IFV-Stinger	1st wave	158	3.16
ICV-Atgm	1st wave	159	3.18
MBT	2nd wave	74	1.48
IFV-TOW	2nd wave	70	1.4
ICV-Atgm	2nd wave	57	1.14
MBT	3rd wave	22	0.44
IFV-TOW	3rd wave	21	0.42
ICV-Atgm	3rd wave	20	0.4
UAV #1		0	0
UAV #2		13	0.26
		760	15.2

Red force	No. of Blues Killed	Mean
Helo	400	8
MBT	207	4.14
120mm Mortar	63	1.26
Anti Tank Mine #1	14	0.28
Anti Tank Mine #2	20	0.4
Anti Tank Mine #3	23	0.46
Inf RPG	17	0.34
Technical ATGM	16	0.32
Total	760	15.2

Figure 26. Analysis on Data Obtained for Design Point 17 and Design Point 21.

The next most significant factor is the sensor classification probability at maximum sensor classification of the MBTs. The MBT's 120 mm main gun can destroy most of the Red forces ground platforms, and has the longest ground engagement range compared to the rest of the ground platforms studied in this thesis. A higher sensor classification probability increases the chance of the MBT engaging adversaries first. This finding suggests that upgrading the MBT's sensor system is more effective in destroying adversary ground platforms, and as suggested by the regression model, there is no need to upgrade the sensing capability of the Stryker-ICVs. Upgrading the MBT's sensing capability improves its own and the entire ground maneuver force's survivability.

UAV speed is identified to be a significant factor that affects ground platform survivability. Increasing UAV speed shortens the duration before it returns to the last scanned location. This reduces the chances of "missing" a target after passing through a surveillance zone. However, it is not realistic to increase a UAV's speed indefinitely as that could decrease the endurance of the UAV, as well as the quality of image transfer.

Interestingly, the Stryker ICV's sensor classification probability at maximum sensor classification range has no effect on the survivability on the ground maneuver forces. This is probably due to the MBTs being more effective in destroying most of the Red agents first.

B. PARTITION TREE ANALYSIS

The R^2 value obtained from partition tree analysis is 0.777, indicating that the partition tree model explains 77.7 percent of the variability in the response (percentage Blue casualties). This is the highest achievable R^2 value obtained after performing four splits. The significant factors identified (in order of significance) are: (1) IFV sensor classification probability, (2) MBT sensor classification probability, and (3) UAV speed. It is also observed that mean percentage of Blue casualties is lower when IFV sensor classification probability is greater than or equal to 0.62, MBT sensor classification probability is greater than or equal to 0.64, and UAV speed is greater than or equal to 57 km/hr. Results from the partition tree analysis compares favorably to the results obtained from regression analysis with an R^2 value of 0.769. The threshold values obtained from partition tree analysis could be used as a reference for determining the degree of improvement that is required. The other insights obtained from the partition tree analysis are similar to those of regression analysis as both analyses identified the same factors in the same order of significance. Figure 27 presents the partition tree.

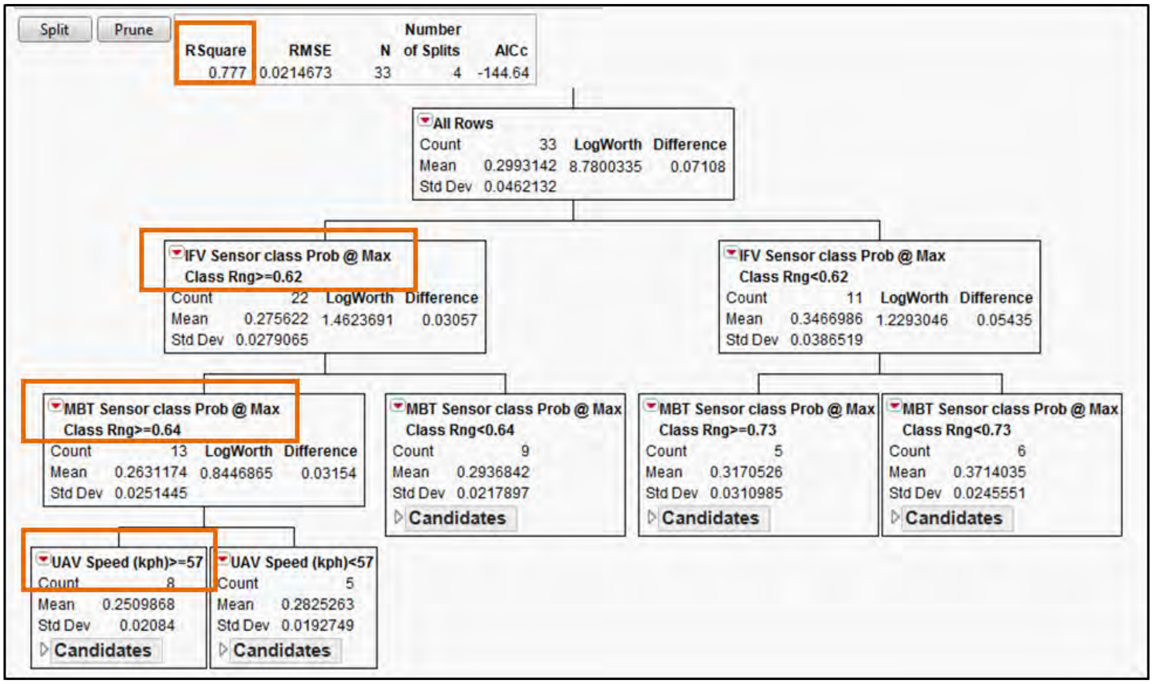


Figure 27. Partition Tree Analysis.

C. ANALYSES SUMMARY

Both the regression analysis for (main effects, two-way interactions, and second order polynomial of the factors) and the partition tree analysis identify the same significant factors with similar R^2 values of 0.769 and 0.777, respectively. This consistency in results verified the correctness of the simulation performed. A summary of the analyses is presented in Table 9.

Table 9. Table Analysis Summary.

Significant Factors (in order of importance)	
Regression Analysis (R^2=0.769)	Partition Tree Analysis (R^2 = 0.777)
IFV Sensor Classification Probability	IFV Sensor Classification Probability
MBT Sensor Classification Probability	MBT Sensor Classification Probability
$(\text{UAV Speed})^2$	UAV Speed
$(\text{IFV sensor classification probability})^2$	
UAV Speed	

VIII. CONCLUSION AND FUTURE RESEARCH

The true performance parameters (weapon engagement range, weapon penetration capability, armor protection thickness, probability of hit, etc.) of systems modeled in this thesis are usually classified. Hence, the parameters of the agents modeled are based on open source references—theses, online reading material, and product brochures—and may not represent the true capability of the systems. The observations and findings based on the MANA scenario created and assumptions made might not reflect what could have happened in the real world. Therefore, the results obtained are only limited to the scope of this thesis. However, this systems engineering approach, using the tailored Waterfall process model, identified and opened up different plausible areas to improve platform survivability—other than focusing on improving the passive protection of ground platforms. The results and findings can be used as references for future work.

A. INSIGHTS

Results of the analysis resemble the outcomes in real maneuver operations. This section describes the insights from the analysis and highlights the importance of performing modeling and simulation. Modeling and simulation provide insights to engineers and decision makers on the feasibility of concepts and provide quantitative values for decision makers' reference.

1. Air Defense Capability for Ground Maneuver Forces

Ground maneuver forces are highly susceptible to airborne attacks. It is observed through simulation runs that attack helicopters are very effective in engaging ground forces. The effectiveness is due to the helicopters' longer sensing and engaging ranges, which makes them less vulnerable to return fire from ground platforms that typically have shorter sensing and engagement ranges. Therefore, if resources are available, ground maneuver forces should try to include air defense assets in the maneuver force to improve their survivability. Regression analysis and partition analysis both identify the classification probability at maximum classification range of both the Bradley IFV, M6 Linebacker and ATGM variants, as the most significant factor affecting the ground platform's survivability. The higher the probability of classifying a target, the faster the M6 Bradley can engage the attack helicopters first. One important finding is that the partition tree analysis is able to identify a threshold value for the decision maker's reference and consideration in determining a target probability to be achieved. With actual performance parameters assigned to the Blue agents, the results can be a good reference for decision makers.

The Abrams MBTs are capable of engaging helicopters as well. However, when compared to the Bradley M6 Linebackers, the Abrams are not as effective because their weapon engagement range is shorter than that of the attack helicopters. These findings may be obvious as it is logical for ground maneuver forces to have air defense capability. However, the question is: how many air defense assets are required? Modeling and simulation can provide a reference quantitative figure for decision makers on this point. The MANA model created can be a baseline model for the analysts to vary platform configurations to determine an appropriate number of air assets.

It is also noted that in the absence of enemy air platforms, the presence of an M6 Bradley would be less significant in improving ground maneuver forces' survivability. Nonetheless, having the M6 Bradley as part of the ground maneuver force is a show of force that can deter adversaries from launching their air platforms.

2. Presence of Main Battle Tanks

The MBT is one of the most important assets in ground maneuver forces. This is due to their long weapon engagement range and their high level of protection against incoming threats. Most often, the MBTs provide ground maneuver forces with protection against adversaries' ground platforms by engaging them first, protecting the platforms protected by less armor. The results indicate that the MBT's sensor classification probability at maximum classification is the next most significant factor. The results indicate that it is not necessary to upgrade the sensing capability for all types of platforms. For example, the regression model and partition tree analysis indicate that upgrading the sensing capability of the Sryker platforms have little effect in improving ground maneuver forces survivability. To improve the ground maneuvering forces' survivability, the priority should be on upgrading MBTs first, followed by the rest of the platforms. This is something decision makers would not know without performing modeling and simulation. When a program to upgrade sensor capabilities for ground platforms encounters a budget reduction, decision makers must determine which platform should be given priority based on quantitative results from simulation runs.

3. Presence of Unmanned Air Vehicles

UAVs can be a valuable asset to ground maneuver forces. The UAVs act as "sensors" for the ground forces, providing them with information, such as terrain features and adversary locations, along the maneuver route. Interestingly the important parameter of the UAV is not the probability of success classification, but UAV speed instead. The speed of the UAV affects the time interval before returning to the same scan zone. There could be instances where Red agents appear after the UAV leaves its last detectable zone. Regression model and partition tree analysis identified UAV speed as a more important factor when compared to sensor classification probability. This outcome is probably because the UAV's flight route is a randomly plotted circular route. The scanning pattern of the UAV can varied to identify the most efficient route, which could reduce the effect on UAV speed, and plausibly reveal other more significant factors of the UAV that could improve ground maneuver forces survivability during maneuver operations. Other limitations in the UAV modeled include assumptions, such as 100 percent communication reliability and absence of electronic warfare. In reality, adversaries might employ jammers to disrupt communications between the UAVs and ground forces, delaying or preventing critical battle information from reaching ground forces.

B. FUTURE RESEARCH

The arms race between lethality and protection is an enduring challenge. Whenever new protection systems are developed, new weapons and munition will be developed to defeat the protection systems, and vice versa. This repetitive cycle seemingly never ends.

There are many other avenues to improve platform survivability, which are not only limited to increasing armor thickness. The proactive approach on the other end focuses on eliminating the source of the threats first, preventing the threats reaching ground platforms. This study shows that adopting a proactive approach is an area worth exploring as the results show positive effects in improving ground platforms' survivability.

It is acknowledged that this study is not exhaustive. However, it can be a starting point for future research, which has the potential of finding other alternatives, and reduces the burden to enhance existing protection systems to improve ground platforms' survivability.

(1) Study on Effectiveness of Unmanned Air Vehicles

The UAV is an important asset to ground maneuver forces. One interesting area to be explored would be developing an effective method to launch and retrieve UAVs by ground maneuver forces "on-the-fly". As pointed out in this study, UAVs play an important role as additional sensors for ground platforms in improving battle field situation awareness. The travel distance by ground platforms in this study is only about 20 km. For longer distances, UAVs launched from base would not be able to provide coverage. Developing a method that allows UAVs to be launched "on-the-fly" would be beneficial to ground maneuver forces.

(2) Study on Effects of Terrain Elevation

The other possible area of research is to incorporate terrain elevation features into the MANA scenario to study the effects of sensor classification probability, sensor detection range, and other sensor attributes. With elevation features added, line of sight of sensors would be affected, and the study could lead to other discoveries.

APPENDIX A. DATA VERIFICATION TEST RESULTS SUMMARY

The first verification is a simulation run observation. Observing the agents during simulation runs allows us to check whether they are responding to different situations according to their behavior attributes. The visual inspection checklist is presented in Table 10.

Table 10. Model Verification – Visual Observation Checklist.

Behavior Settings	Agent Behavior	Visual Observation
Movement Settings	Blue agents' movements follow way points.	√
	Blue agents maneuver in correct formation.	√
	Blue agents' speed reduced when contacted.	√
	Red agents move toward Blue agent during engagement.	√
	Blue UAV hovering near to red forces when detected.	√
	Red Helicopters' movement follow way points	√
Communication Settings	Blue UAV communicates to Blue artillery when Red agents are detected.	√
	Red FO communicates to Red mortar when Blue agents are detected.	√
Engagement Settings	Blue and Red forces engaging at one another when in range.	√
Concealment settings	Red agents are in 100% concealment before they take shot at Blue agents.	√
	Blue UAV cannot detect red agents before they take shot at blue agents.	√
	Blue UAV can detect red agents when they take shot at Blue agents.	√
Sensor Settings	Using the "View Squad Situation Awareness" feature to check whether agents can detect each other when they are in their sensing ranges.	√

The second verification is to check the data generated by MANA to verify whether the agents are behaving correctly during engagement. Fifty simulation runs on the model created were simulated, and the data set generated was used for verification.

A snapshot of the casualty location file for a single simulation run is presented in Figure 28. The Cas Squad column (agents killed) is compared against the Sqd name column (Killer agents), and checked against the killer victim matrix to verify the correctness of engagement. The Agent State column is checked to verify that the agents are in the correct trigger state. The Weapon Class column and Weapon ID column are checked to verify that the right type of weapon is used by the "killer" agent on the casualty. In MANA, each weapon is set to engage a specific class of platforms. Lastly, the Shooter Alleg column is checked to verify that there is no collateral damage as per set in the model (1 = Blue Agent, 2 = Red Agent). Location of casualties and shooters, denoted by x-casualty and y casualty, and x-shooter and y-shooter respectively are not checked as they are not representative of the agents' behavior.

The data verification test verifies that the model is created correctly as there is no abnormality in the data captured and generated by MANA.

# MANA Casualty Location Results File
# Version: 5.01.05
# Machine Name: TCH-HP
# Rur 10:13:13 PM
RandSeed= 1194237488

ID	x-casualty	y-casualty	time	Cas Squad	Cas Squad ID	Cas alleg	sub squad	state	shooter ID	Squad ID	Sqd name	weapon class	weapon ID	x-shooter	y-shooter	shooter alleg
3	14343	9390	39[illegible]	Blue M1A2 MBT 1st Wave	1	1	0	Contact State 1	25	10	Red 120mm Mortar	Primary	1	14061	4623	2
0	14239	9317	440	Blue M1A2 MBT 1st Wave	1	1	0	Contact State 1	26	10	Red 120mm Mortar	Primary	1	13887	4579	2
1	14492	9410	49[illegible]	Blue M1A2 MBT 1st Wave	1	1	0	Contact State 1	27	10	Red 120mm Mortar	Primary	1	13243	4862	2
11	14538	9571	541	Blue Stryker ATGM (1st wave)	3	1	0	Default State	29	13	RED HELO	Primary	1	8748	6545	2
29	8788	6556	542	RED HELO	13	2	0	Default State	7	2	Blue IFV M6 LineBacker	Primary	3	14287	9346	1
30	8307	6489	57[illegible]	RED HELO	13	2	0	Default State	5	2	Blue IFV M6 LineBacker	Primary	3	14228	9322	1
2	14327	9344	580	Blue M1A2 MBT 1st Wave	1	1	0	Contact State 1	26	10	Red 120mm Mortar	Primary	1	13887	4579	2

Figure 28. Model Verification – Data Inspection.

Positive results from the two types of model verification tests verify that the model is modeled correctly, and the model is ready for further simulations.

APPENDIX B. DESIGN POINTS SIMULATION RESULTS SUMMARY

The results of the simulation runs for the 33 design points identified using the NOLH design of experiments methodology are summarized in Table 11. A total of eight performance parameters are being studied, and the mean, standard deviation, and 95 percent lower and upper confidence of the mean of 50 replications are being tabulated. JMP is the statistical program used to generate the results. The eight performance parameters are:

1. Number of Blue casualties (Blue Cas)
2. Percentage of Blue casualties (% Blue Cas)
3. Number of Red casualties (Red Cas)
4. Exchange Ratio (Kill Ratio)
5. Force Exchange Ratio (FER)
6. Number of times Blue completes mission for fight-to-finish scenario (Blue Goal, Fight-to-the-finish)
7. Number of times Blue completes mission with casualties suffered less than 50 percent (Blue Goal, Casualty < 50%)
8. Time to complete mission (time to complete mission)

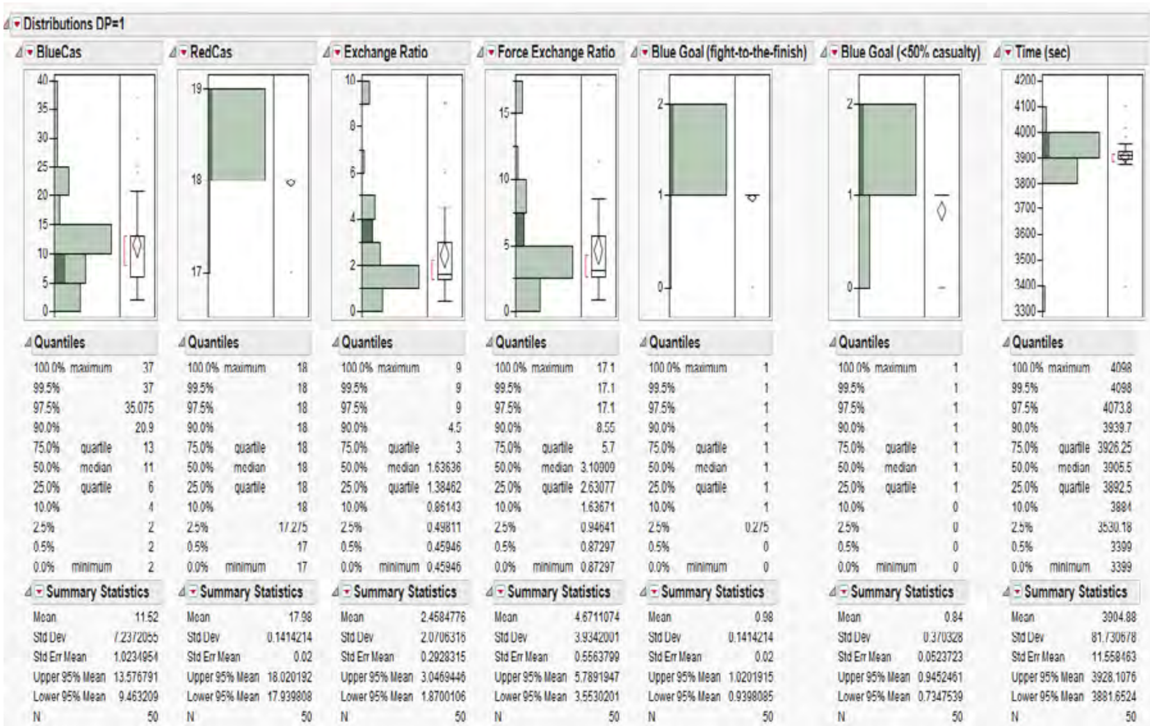
The distribution plots of individual design points in this appendix provide additional information, such as box plots, occurrences at different quantiles, and standard error mean and median of each design points.

The distribution plots for Exchange Ratio and Force Exchange Ratio are also included. Both performance parameters present a high standard deviation. This is attributed to the variability in number of Blue casualties, as the number of Red casualties for each design point is almost constant with values of either 18 or 19. Since the variability is largely due to Blue casualties, the focus would be on analyzing Blue casualties. Therefore, the Exchange Ratio and Force Exchange Ratio are not studied in great detail in this thesis.

Table 11. Results for Simulation Runs for 33 Design Points.

	32 to 81 kph	Classification Probability (0.5 to 0.85) @ Maximum Classify Range																			
Design Point	UAV Speed (kph)	UAV Sensor	MBT Sensor	IFV Sensor	ICV Sensor	Blue Cas (mean)	Std Dev	Lower 95% Mean	Upper 95% Mean	% Blue Cas (mean)	Std Dev	Lower 95% Mean	Upper 95% Mean	Red Cas (mean)	Std Dev	Lower 95% Mean	Upper 95% Mean	Kill Ratio	Std Dev	Lower 95% Mean	Upper 95% Mean
1	81	0.65	0.57	0.81	0.72	11.52	7.237	9.46	13.57	0.303	0.190	0.249	0.357	17.98	0.141	17.90	18.20	2.46	2.071	1.87	3.05
2	76	0.54	0.63	0.66	0.57	11.58	7.077	9.57	13.59	0.305	0.186	0.252	0.358	18.98	0.141	18.94	19.02	2.33	1.514	1.90	2.76
3	75	0.82	0.55	0.51	0.71	14.14	8.127	11.83	16.45	0.372	0.214	0.311	0.433	18.88	0.480	18.74	19.02	1.90	1.471	1.48	2.32
4	60	0.85	0.64	0.83	0.55	9.36	5.198	7.90	10.86	0.247	0.137	0.208	0.286	19.00	0.000	19.00	19.00	2.96	2.902	2.14	3.79
5	78	0.66	0.58	0.74	0.75	10.56	6.609	8.68	12.44	0.278	0.174	0.228	0.327	18.96	0.283	18.88	19.04	3.00	3.561	1.99	4.01
6	79	0.61	0.60	0.65	0.58	12.46	7.034	10.46	14.46	0.328	0.185	0.275	0.381	18.98	0.141	18.94	19.02	2.28	1.945	1.73	2.83
7	66	0.84	0.59	0.50	0.73	13.18	8.975	10.63	15.73	0.347	0.236	0.280	0.414	18.94	0.240	18.87	19.01	2.55	2.953	1.71	3.39
8	58	0.83	0.62	0.82	0.59	9.98	7.260	7.92	12.04	0.263	0.191	0.208	0.317	18.60	2.688	17.84	19.36	3.19	2.997	2.33	4.04
9	64	0.58	0.69	0.75	0.61	10.24	6.811	8.30	12.18	0.269	0.179	0.218	0.321	18.68	2.123	18.07	19.28	2.78	2.104	2.18	3.38
10	69	0.60	0.74	0.58	0.69	10.48	6.463	8.84	12.32	0.276	0.170	0.233	0.324	19.00	0.000	19.00	19.00	2.71	2.080	2.12	3.31
11	67	0.76	0.84	0.62	0.52	9.58	5.191	8.10	11.06	0.252	0.137	0.213	0.291	19.00	0.000	19.00	19.00	2.54	1.289	2.18	2.91
12	70	0.73	0.83	0.76	0.84	9.88	7.300	7.81	11.95	0.260	0.192	0.206	0.314	19.00	0.000	19.00	19.00	3.17	2.900	2.34	3.99
13	61	0.57	0.70	0.71	0.54	9.96	6.224	8.19	11.73	0.262	0.164	0.216	0.309	19.00	0.000	19.00	19.00	3.15	3.627	2.12	4.18
14	73	0.63	0.81	0.55	0.70	12.32	7.649	10.15	14.49	0.324	0.201	0.267	0.381	18.94	0.424	18.82	19.06	2.25	1.659	1.77	2.72
15	63	0.80	0.82	0.63	0.50	10.46	7.869	8.22	12.70	0.275	0.207	0.216	0.334	18.88	0.849	18.64	19.12	3.31	3.655	2.27	4.35
16	72	0.71	0.85	0.78	0.82	8.66	5.025	7.23	10.09	0.228	0.132	0.190	0.266	19.00	0.000	19.00	19.00	3.19	2.714	2.42	3.96
17	57	0.68	0.68	0.68	0.68	8.12	4.945	6.73	9.55	0.214	0.130	0.177	0.251	19.00	0.000	19.00	19.00	3.65	3.679	2.60	4.69
18	32	0.70	0.78	0.54	0.63	13.50	8.744	11.03	16.01	0.356	0.230	0.290	0.421	18.94	0.240	18.87	19.01	2.47	2.889	1.64	3.29
19	37	0.81	0.72	0.69	0.78	11.70	7.514	9.56	13.84	0.308	0.198	0.252	0.364	18.98	0.141	18.93	19.02	2.43	1.870	1.90	2.96
20	38	0.53	0.80	0.84	0.64	10.44	7.332	8.36	12.52	0.275	0.193	0.220	0.329	19.00	0.000	19.00	19.00	3.25	3.281	2.31	4.18
21	53	0.50	0.71	0.52	0.80	15.20	9.714	12.44	17.96	0.400	0.256	0.327	0.473	18.92	0.444	18.79	19.05	2.04	1.602	1.59	2.50
22	35	0.69	0.77	0.61	0.60	12.62	7.830	10.40	14.85	0.332	0.206	0.274	0.391	19.00	0.000	19.00	19.00	2.74	3.659	1.70	3.78
23	34	0.74	0.75	0.70	0.77	11.22	6.212	9.45	12.99	0.295	0.163	0.249	0.342	19.00	0.000	19.00	19.00	2.49	1.916	1.94	3.03
24	47	0.51	0.76	0.85	0.62	10.50	5.437	8.95	12.05	0.276	0.143	0.236	0.317	19.00	0.000	19.00	19.00	2.84	3.134	1.95	3.74
25	55	0.52	0.73	0.53	0.76	11.28	6.390	9.48	13.12	0.297	0.168	0.249	0.345	18.98	0.141	18.94	19.02	2.57	2.722	1.79	3.34
26	49	0.77	0.66	0.60	0.74	12.98	6.924	11.01	14.95	0.342	0.182	0.290	0.393	19.00	0.000	19.00	19.00	2.04	1.543	1.60	2.47
27	44	0.75	0.61	0.77	0.66	10.80	5.393	9.29	12.35	0.285	0.142	0.244	0.325	18.98	0.141	18.94	19.02	2.46	2.629	1.72	3.21
28	46	0.59	0.51	0.73	0.83	10.28	6.433	8.45	12.11	0.271	0.169	0.222	0.319	18.94	0.240	18.87	19.01	2.88	2.949	2.04	3.72
29	43	0.62	0.52	0.59	0.51	14.06	8.105	11.76	16.36	0.370	0.213	0.309	0.431	18.84	0.681	18.65	19.03	1.96	1.692	1.48	2.45
30	52	0.78	0.65	0.64	0.81	9.82	5.965	8.12	11.52	0.258	0.157	0.214	0.303	18.86	0.990	18.58	19.14	2.66	1.696	2.18	3.14
31	40	0.72	0.54	0.80	0.65	12.08	6.067	10.36	13.80	0.318	0.160	0.273	0.363	19.00	0.000	19.00	19.00	2.44	2.838	1.63	3.24
32	50	0.55	0.53	0.72	0.85	11.14	6.132	9.42	12.90	0.294	0.161	0.248	0.339	19.00	0.000	19.00	19.00	2.65	2.963	1.80	3.49
33	41	0.64	0.50	0.57	0.53	15.12	8.248	12.78	17.46	0.398	0.217	0.336	0.459	18.86	0.729	18.65	19.07	2.01	2.680	1.24	2.77

	32 to 81 kph	Classification Probability (0.5 to 0.85) @ Maximum Classify Range																			
Design Point	UAV Speed (kph)	UAV Sensor	MBT Sensor	IFV Sensor	ICV Sensor	FER	Std Dev	Lower 95% Mean	Upper 95% Mean	Blue Goal (fight to finish)	Std Dev	Lower 95% Mean	Upper 95% Mean	Blue Goal (Casualty <50%)	Std Dev	Lower 95% Mean	Upper 95% Mean	Time to complete mission	Std Dev	Lower 95% Mean	Upper 95% Mean
1	81	0.65	0.57	0.81	0.72	4.67	3.934	3.55	5.79	0.98	0.141	0.94	1.00	0.84	0.370	0.73	0.95	3904.88	81.73	3881.65	3928.11
2	76	0.54	0.63	0.66	0.57	4.43	2.877	3.61	5.25	0.98	0.141	0.94	1.00	0.84	0.370	0.73	0.95	4036.84	861.17	3792.10	4281.58
3	75	0.82	0.55	0.51	0.71	3.61	2.795	2.81	4.40	0.94	0.240	0.87	1.00	0.78	0.418	0.66	0.90	4150.98	1207.40	3807.84	4494.12
4	60	0.85	0.64	0.83	0.55	5.62	5.514	4.19	4.06	1.00	0.000	1.00	1.00	0.92	0.274	0.84	1.00	3924.26	37.52	3913.60	3934.92
5	78	0.66	0.58	0.74	0.75	5.70	6.766	3.78	7.63	1.00	0.000	1.00	1.00	0.90	0.303	0.81	0.99	3921.88	44.12	3909.34	3934.42
6	79	0.61	0.60	0.65	0.58	4.33	3.695	3.28	5.38	0.98	0.141	0.94	1.00	0.86	0.351	0.76	0.96	3905.44	52.40	3890.55	3920.33
7	66	0.84	0.59	0.50	0.73	4.85	5.610	3.25	6.45	0.92	0.274	0.84	0.99	0.80	0.404	0.69	0.91	4407.98	1666.19	3934.45	4881.51
8	58	0.83	0.62	0.82	0.59	6.05	5.694	4.33	7.67	0.98	0.141	0.94	1.00	0.92	0.274	0.84	1.00	3866.06	441.62	3740.55	3991.57
9	64	0.58	0.69	0.75	0.61	5.28	3.998	4.15	6.42	0.98	0.141	0.94	1.00	0.90	0.303	0.91	0.99	3910.34	114.49	3877.80	3942.88
10	69	0.60	0.74	0.58	0.69	5.15	3.952	4.03	6.28	0.98	0.141	0.94	1.00	0.92	0.274	0.84	1.00	4037.26	861.14	3792.53	4281.99
11	67	0.76	0.84	0.62	0.52	4.83	2.450	4.14	5.53	1.00	0.000	1.00	1.00	0.92	0.274	0.84	1.00	3916.02	32.35	3906.83	3925.21
12	70	0.73	0.83	0.76	0.84	6.02	5.511	4.46	7.59	0.98	0.141	0.94	1.00	0.88	0.328	0.79	0.97	4042.70	860.93	3798.03	4287.37
13	61	0.57	0.70	0.71	0.54	5.99	6.891	4.03	7.95	1.00	0.000	1.00	1.00	0.92	0.274	0.84	1.00	3923.26	35.19	3913.26	3933.26
14	73	0.63	0.81	0.55	0.70	4.27	3.151	3.37	5.16	0.98	0.141	0.94	1.00	0.82	0.388	0.71	0.93	3921.98	71.72	3901.60	3942.36
15	63	0.80	0.82	0.63	0.50	6.29	6.944	4.31	8.26	0.96	0.198	0.90	1.00	0.88	0.328	0.79	0.97	4171.20	1202.93	3829.33	4513.07
16	72	0.71	0.85	0.78	0.82	6.06	5.157	4.59	7.52	1.00	0.000	1.00	1.00	0.96	0.198	0.90	1.00	3922.40	43.95	3909.91	3934.89
17	57	0.68	0.68	0.68	0.68	6.93	6.990	4.95	8.92	1.00	0.000	1.00	1.00	0.96	0.198	0.90	1.00	3930.94	58.26	3914.38	3947.50
18	32	0.70	0.78	0.54	0.63	4.68	5.489	3.12	6.24	0.96	0.198	0.90	1.00	0.78	0.418	0.66	0.90	4169.22	1203.24	3827.26	4511.18
19	37	0.81	0.72	0.69	0.78	4.62	3.553	3.61	5.63	0.98	0.141	0.94	1.00	0.88	0.328	0.79	0.97	4039.96	860.84	3795.31	4284.61
20	38	0.53	0.80	0.84	0.64	6.17	6.234	4.40	7.94	1.00	0.000	1.00	1.00	0.86	0.351	0.76	0.96	3923.58	40.47	3912.08	3935.08
21	53	0.50	0.71	0.52	0.80	3.88	3.044	3.02	4.75	0.96	0.198	0.90	1.00	0.70	0.463	0.57	0.83	4045.14	861.89	3800.20	4290.09
22	35	0.69	0.77	0.61	0.60	5.21	6.952	2.24	7.19	0.98	0.141	0.94	1.00	0.78	0.418	0.66	0.90	4032.90	861.49	3788.07	4277.73
23	34	0.74	0.75	0.70	0.77	4.72	3.640	3.69	5.76	1.00	0.000	1.00	1.00	0.92	0.274	0.84	1.00	3912.78	29.79	3904.31	3921.25
24	47	0.51	0.76	0.85	0.62	5.40	5.954	3.80	7.08	0.98	0.141	0.94	1.00	0.98	0.141	0.94	1.00	4041.00	860.85	3796.35	4285.65
25	55	0.52	0.73	0.53	0.76	4.87	5.171	3.40	6.34	1.00	0.000	1.00	1.00	0.86	0.351	0.76	0.96	3909.44	27.25	3901.70	3917.18
26	49	0.77	0.66	0.60	0.74	3.87	2.931	3.04	4.70	1.00	0.000	1.00	1.00	0.84	0.370	0.73	0.05	3920.74	53.01	3905.67	3935.81
27	44	0.75	0.61	0.77	0.66	4.68	4.995	3.26	6.10	0.98	0.141	0.94	1.00	0.98	0.141	0.94	1.00	4038.28	860.96	3793.60	4282.96
28	46	0.59	0.51	0.73	0.83	5.47	5.603	3.88	7.06	0.98	0.141	0.94	1.00	0.96	0.198	0.90	1.00	4053.48	862.32	3808.41	4298.55
29	43	0.62	0.52	0.59	0.51	3.73	3.215	2.82	4.65	0.94	0.240	0.87	1.00	0.84	0.370	0.73	0.95	4278.96	1461.44	3863.62	4694.30
30	52	0.78	0.65	0.64	0.81	5.06	3.222	4.14	5.97	0.98	0.141	0.94	1.00	0.94	0.240	0.87	1.00	4038.80	860.76	3794.17	4283.43
31	40	0.72	0.54	0.80	0.65	4.63	5.392	3.10	6.16	1.00	0.000	1.00	1.00	0.88	0.328	0.79	0.97	3909.76	35.51	3899.67	3919.85
32	50	0.55	0.53	0.72	0.85	5.03	5.630	3.43	6.63	1.00	0.000	1.00	1.00	0.86	0.351	0.76	0.96	3916.64	35.38	3906.59	3926.69
33	41	0.64	0.50	0.57	0.53	3.81	5.092	2.36	5.26	0.92	0.274	0.84	1.00	0.70	0.463	0.57	0.83	4401.76	1667.89	3927.75	4875.77

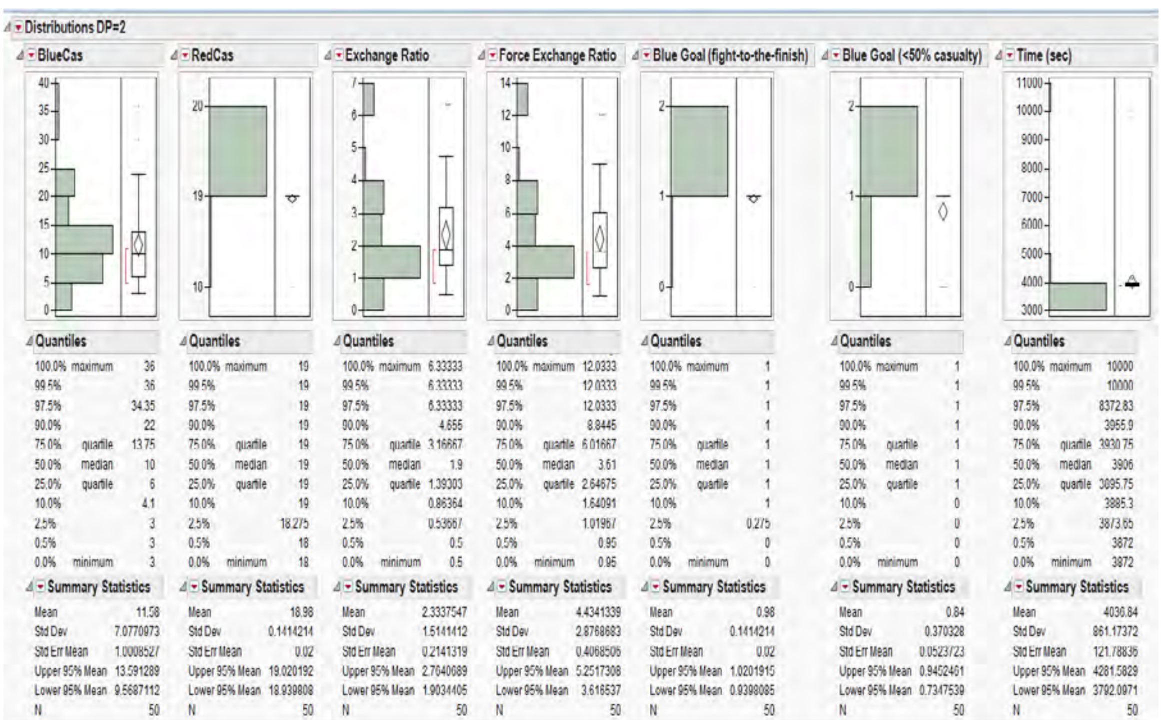


Distributions DP=1

Quantiles	BlueCas	RedCas	Exchange Ratio	Force Exchange Ratio	Blue Goal (fight-to-the-finish)	Blue Goal (<50% casualty)	Time (sec)
100.0% maximum	37	18	9	17.1	1	1	4098
99.5%	37	18	9	17.1	1	1	4098
97.5%	35.075	18	9	17.1	1	1	4073.8
90.0%	20.9	18	4.5	8.55	1	1	3939.7
75.0% quartile	13	18	3	5.7	1	1	3926.25
50.0% median	11	18	1.63636	3.10909	1	1	3906.5
25.0% quartile	6	18	1.38462	2.63077	1	1	3882.5
10.0%	4	18	0.86143	1.63671	1	0	3884
2.5%	2	17.275	0.49811	0.94641	0.275	0	3530.18
0.5%	2	17	0.45946	0.87297	0	0	3399
0.0% minimum	2	17	0.45946	0.87297	0	0	3399

Summary Statistics	BlueCas	RedCas	Exchange Ratio	Force Exchange Ratio	Blue Goal (fight-to-the-finish)	Blue Goal (<50% casualty)	Time (sec)
Mean	11.52	17.98	2.4584776	4.6711074	0.98	0.84	3904.88
Std Dev	7.2372055	0.1414214	2.0706316	3.9342001	0.1414214	0.370328	81.730678
Std Err Mean	1.0234951	0.02	0.2928315	0.5563799	0.02	0.0523723	11.558463
Upper 95% Mean	13.576791	18.020192	3.0469446	5.7891947	1.0201915	0.9452461	3928.1076
Lower 95% Mean	9.463209	17.939808	1.8700106	3.5530201	0.9398085	0.7347539	3881.6524
N	50	50	50	50	50	50	50

Figure 29. Distribution Plots for Design Point 1.



Distributions DP=2

Quantiles	BlueCas	RedCas	Exchange Ratio	Force Exchange Ratio	Blue Goal (fight-to-the-finish)	Blue Goal (<50% casualty)	Time (sec)
100.0% maximum	36	19	6.33333	12.0333	1	1	10000
99.5%	36	19	6.33333	12.0333	1	1	10000
97.5%	34.35	19	6.33333	12.0333	1	1	8372.83
90.0%	22	19	4.655	8.8445	1	1	3955.9
75.0% quartile	13.75	19	3.16667	6.01667	1	1	3930.75
50.0% median	10	19	1.9	3.61	1	1	3906
25.0% quartile	6	19	1.39303	2.64675	1	1	3895.75
10.0%	4.1	19	0.86364	1.64091	1	0	3885.3
2.5%	3	18.275	0.53667	1.01967	0.275	0	3873.65
0.5%	3	18	0.5	0.95	0	0	3872
0.0% minimum	3	18	0.5	0.95	0	0	3872

Summary Statistics	BlueCas	RedCas	Exchange Ratio	Force Exchange Ratio	Blue Goal (fight-to-the-finish)	Blue Goal (<50% casualty)	Time (sec)
Mean	11.58	18.98	2.3337547	4.4341339	0.98	0.84	4036.84
Std Dev	7.0770973	0.1414214	1.5141412	2.8768683	0.1414214	0.370328	861.17372
Std Err Mean	1.0008527	0.02	0.2141319	0.4068506	0.02	0.0523723	121.78836
Upper 95% Mean	13.591289	19.020192	2.7640689	5.2517308	1.0201915	0.9452461	4281.5829
Lower 95% Mean	9.5687112	18.939808	1.9034405	3.616537	0.9398085	0.7347539	3792.0971
N	50	50	50	50	50	50	50

Figure 30. Distribution Plots for Design Point 2.

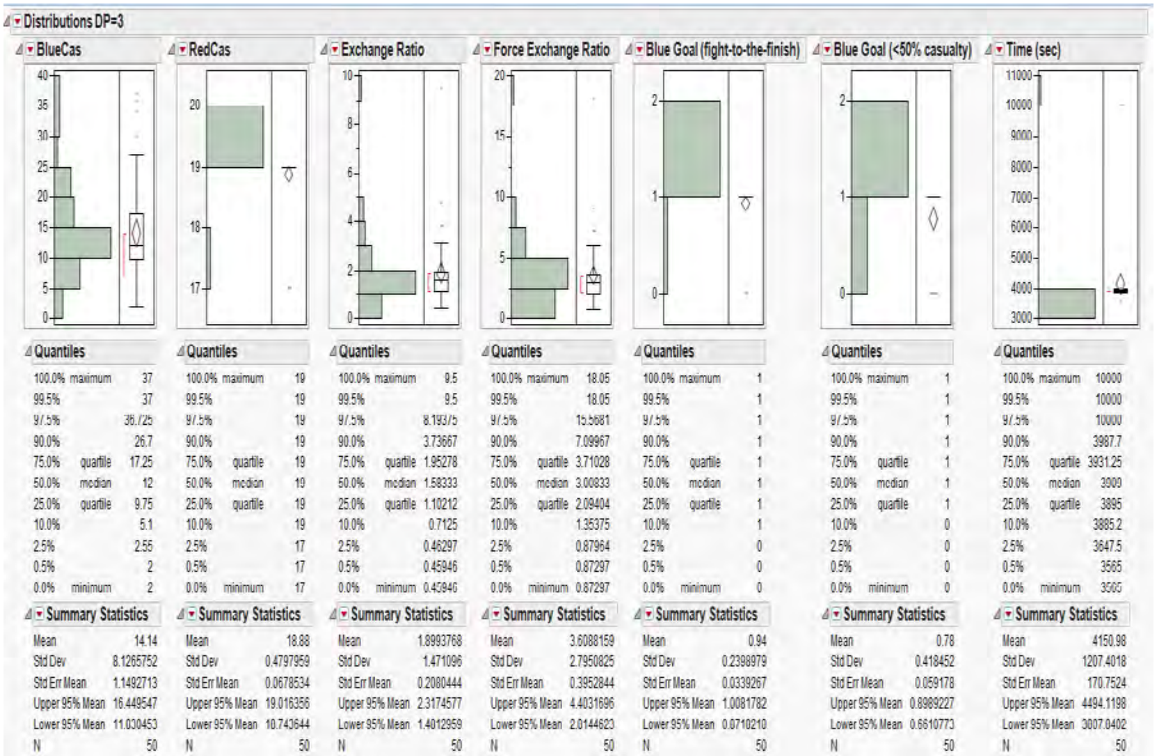


Figure 31. Distribution Plots for Design Point 3.

Figure 32. Distribution Plots for Design Point 4.

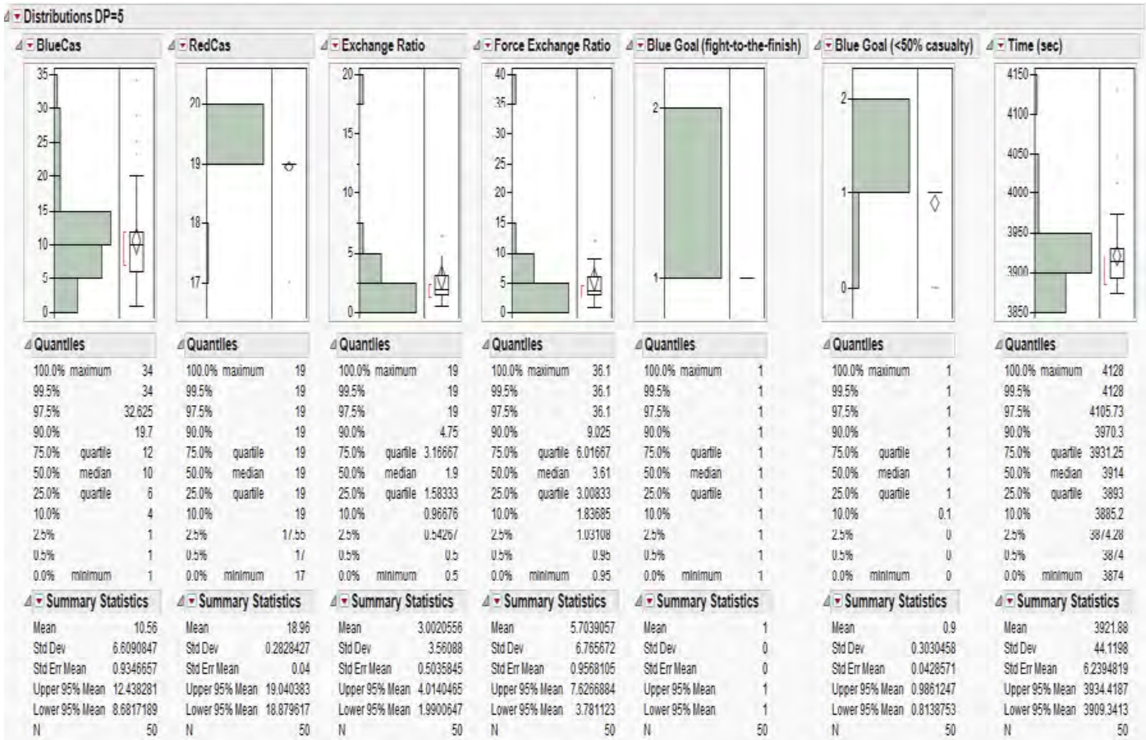
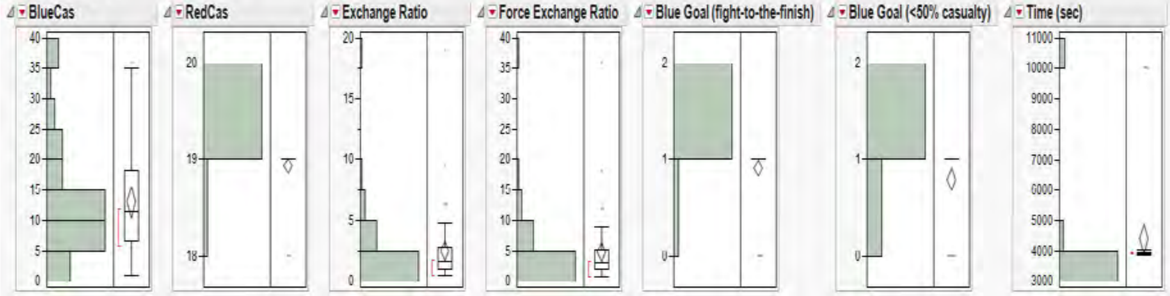


Figure 33. Distribution Plots for Design Point 5.

Figure 34. Distribution Plots for Design Point 6.

Distributions DP=7

	BlueCas	RedCas	Exchange Ratio	Force Exchange Ratio	Blue Goal (fight-to-the-finish)	Blue Goal (<50% casualty)	Time (sec)



Quantiles

		BlueCas	RedCas	Exchange Ratio	Force Exchange Ratio	Blue Goal (fight-to-the-finish)	Blue Goal (<50% casualty)	Time (sec)
100.0%	maximum	36	19	19	36.1	1	1	10000
99.5%		36	19	19	36.1	1	1	10000
97.5%		36	19	16.3875	31.1363	1	1	10000
90.0%		28.6	19	6.175	11.7325	1	1	4048.7
75.0%	quartile	18.25	19	2.82738	5.37202	1	1	3956.25
50.0%	median	11.5	19	1.6553	3.14508	1	1	3915
25.0%	quartile	6.75	19	1.04167	1.97917	1	1	3892.5
10.0%		3.1	19	0.66666	1.26474	1	0	3885.1
2.5%		1.275	18	0.5	0.95	0	0	3870.65
0.5%		1	18	0.5	0.95	0	0	3869
0.0%	minimum	1	18	0.5	0.95	0	0	3869

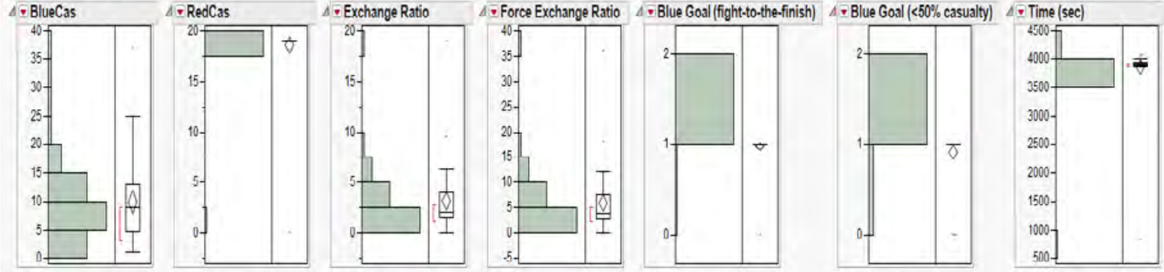
Summary Statistics

	BlueCas	RedCas	Exchange Ratio	Force Exchange Ratio	Blue Goal (fight-to-the-finish)	Blue Goal (<50% casualty)	Time (sec)
Mean	13.18	18.94	2.5541222	4.8528322	0.92	0.8	4407.98
Std Dev	8.9754541	0.2398979	2.9528524	5.6104106	0.2740475	0.404061	1666.1019
Std Err Mean	1.2693209	0.0339267	0.4175964	0.7934331	0.0387562	0.0571429	235.63511
Upper 95% Mean	15.730796	19.008178	3.3933136	6.4472958	0.9978834	0.9148329	4881.5065
Lower 95% Mean	10.629204	18.871822	1.7149308	3.2583686	0.8421166	0.6851671	3934.4535
N	50	50	50	50	50	50	50

Figure 35. Distribution Plots for Design Point 7.

Distributions DP=8

	BlueCas	RedCas	Exchange Ratio	Force Exchange Ratio	Blue Goal (fight-to-the-finish)	Blue Goal (<50% casualty)	Time (sec)



Quantiles

		BlueCas	RedCas	Exchange Ratio	Force Exchange Ratio	Blue Goal (fight-to-the-finish)	Blue Goal (<50% casualty)	Time (sec)
100.0%	maximum	37	19	19	36.1	1	1	4080
99.5%		37	19	19	36.1	1	1	4080
97.5%		35.075	19	16.3875	31.1363	1	1	4072.58
90.0%		18	19	6.33333	12.0333	1	1	3998.4
75.0%	quartile	13	19	4.0375	7.67125	1	1	3948.5
50.0%	median	9	19	2.11111	4.01111	1	1	3913.5
25.0%	quartile	4.75	19	1.46154	2.77692	1	1	3889.5
10.0%		3	19	1.05556	2.00556	1	1	3878.2
2.5%		1.275	4.95	0.17417	0.33092	0.275	0	1661.75
0.5%		1	0	0	0	0	0	823
0.0%	minimum	1	0	0	0	0	0	823

Summary Statistics

	BlueCas	RedCas	Exchange Ratio	Force Exchange Ratio	Blue Goal (fight-to-the-finish)	Blue Goal (<50% casualty)	Time (sec)
Mean	9.98	18.5	3.1856099	6.0528587	0.98	0.92	3866.06
Std Dev	7.2604323	2.6878411	2.9969539	5.6942124	0.1414214	0.2740475	441.61053
Std Err Mean	1.0267802	0.3801181	0.4238333	0.8052832	0.02	0.0387562	62.454009
Upper 95% Mean	12.043392	19.363876	4.0373347	7.670936	1.0201915	0.9978834	3991.566
Lower 95% Mean	7.916608	17.836124	2.333885	4.4343815	0.9398085	0.8421166	3740.554
N	50	50	50	50	50	50	50

Figure 36. Distribution Plots for Design Point 8.

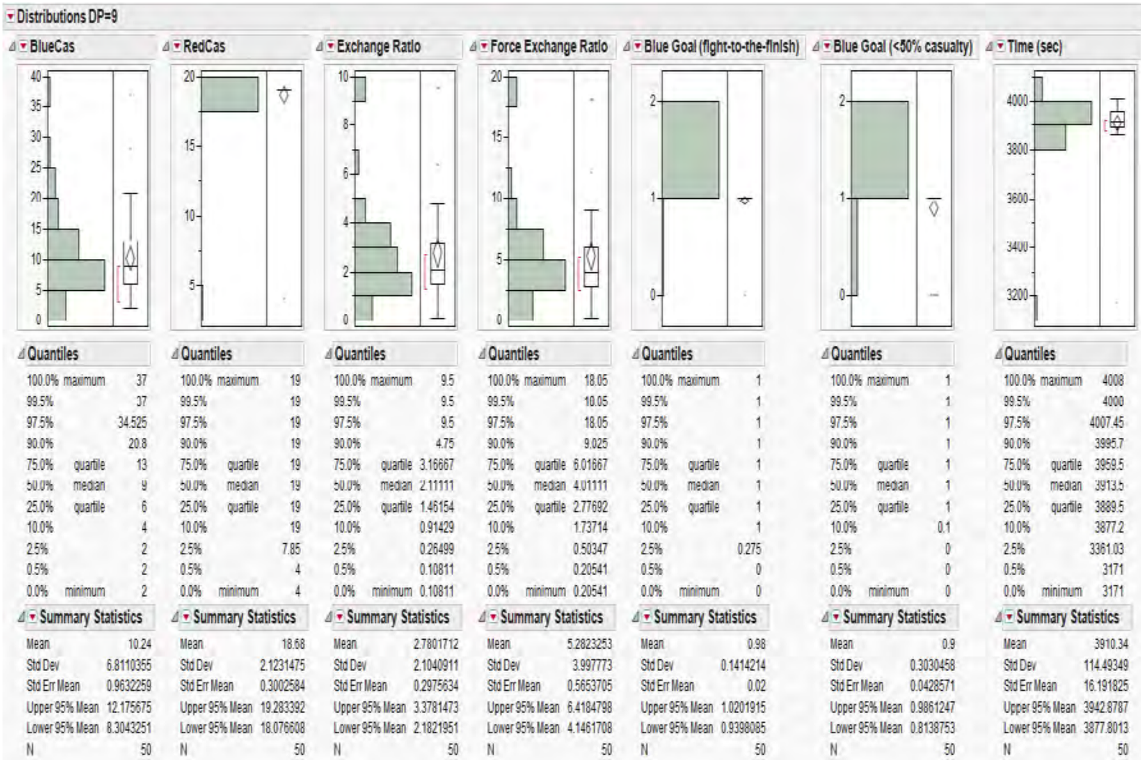


Figure 37. Distribution Plots for Design Point 9.

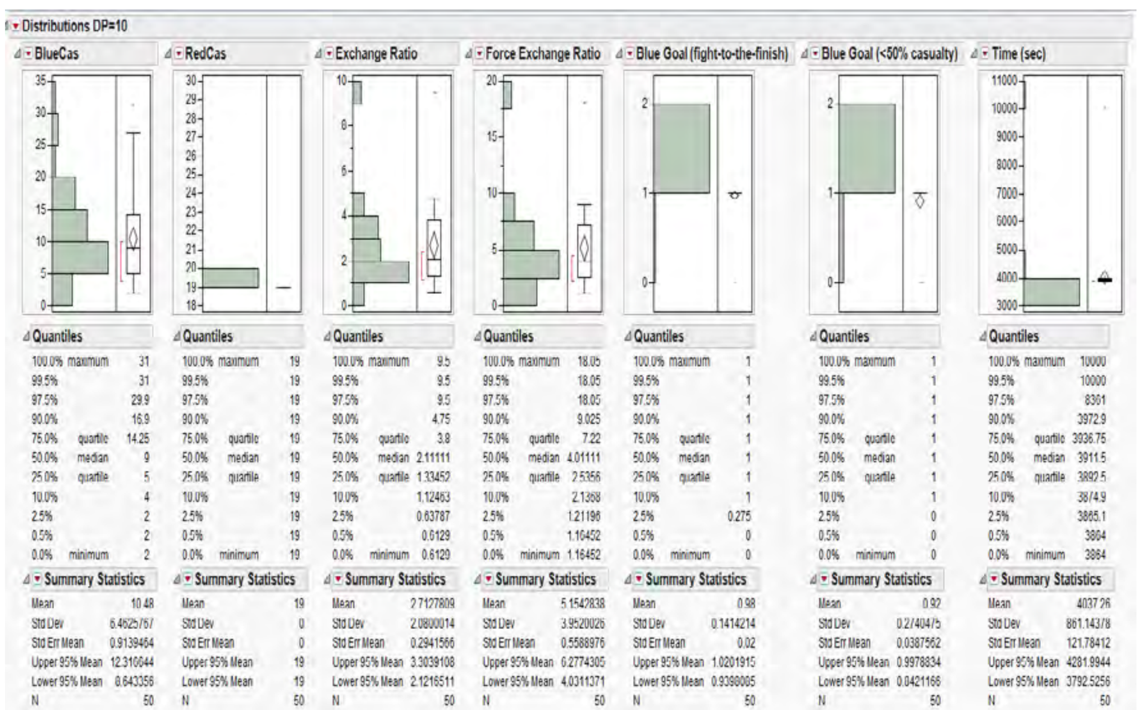


Figure 38. Distribution Plots for Design Point 10.

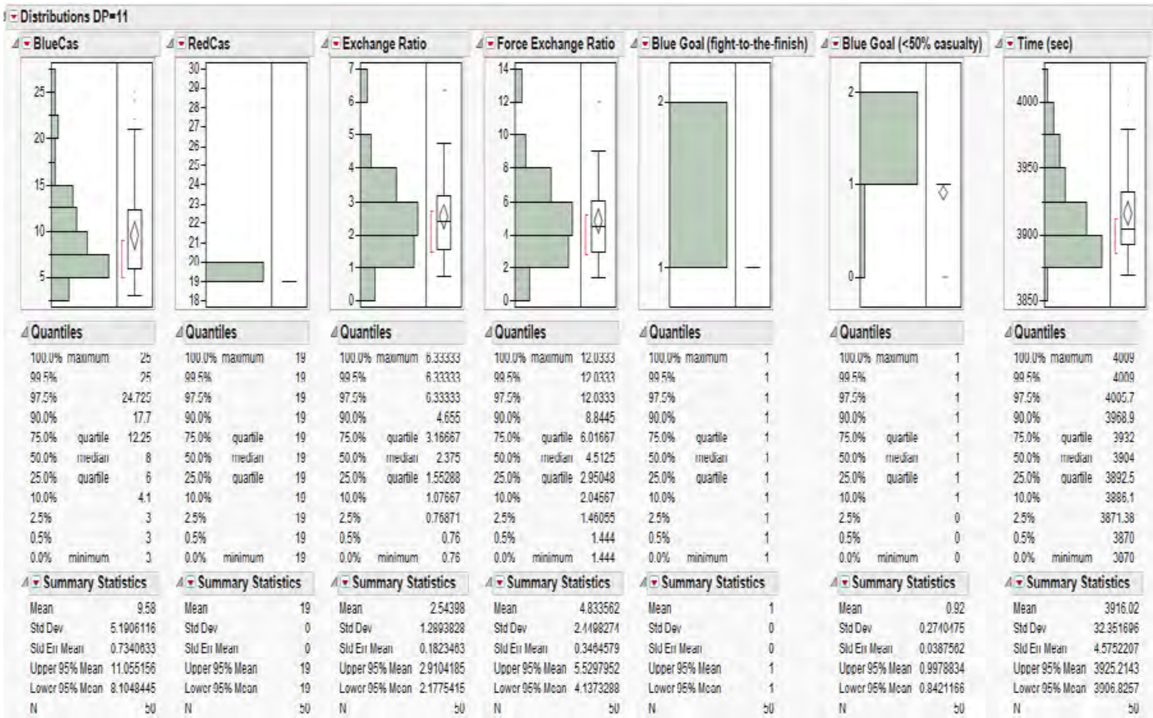


Figure 39. Distribution Plots for Design Point 11.

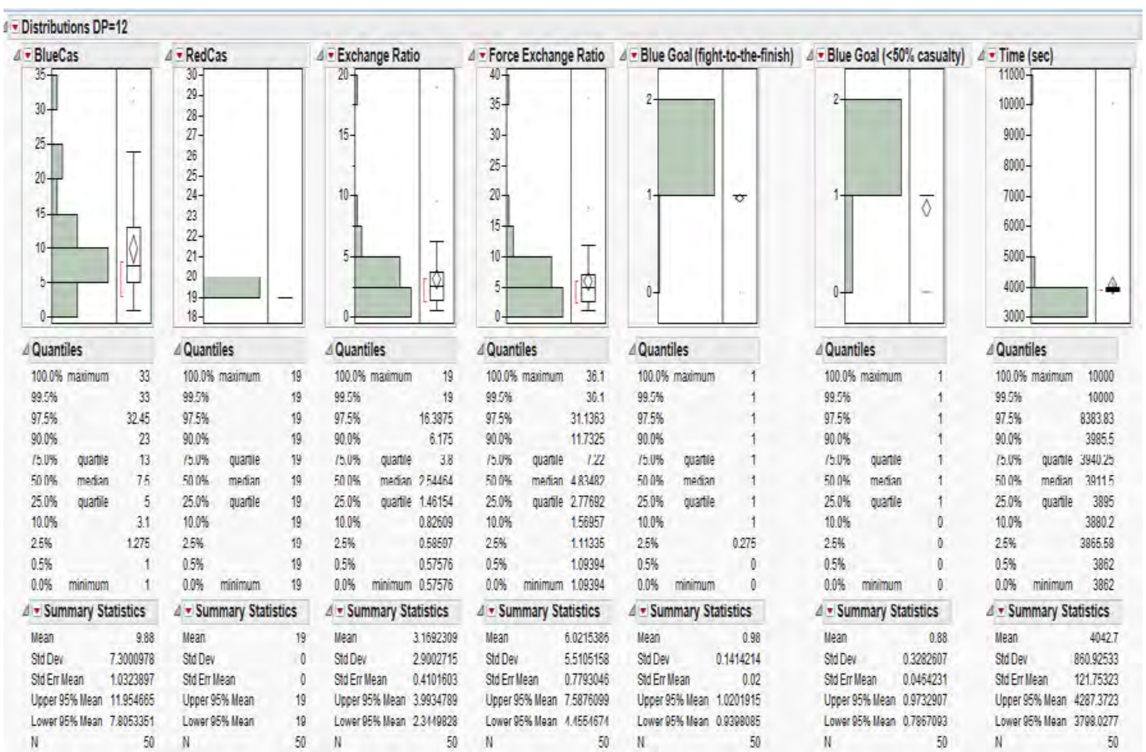


Figure 40. Distribution Plots for Design Point 12.

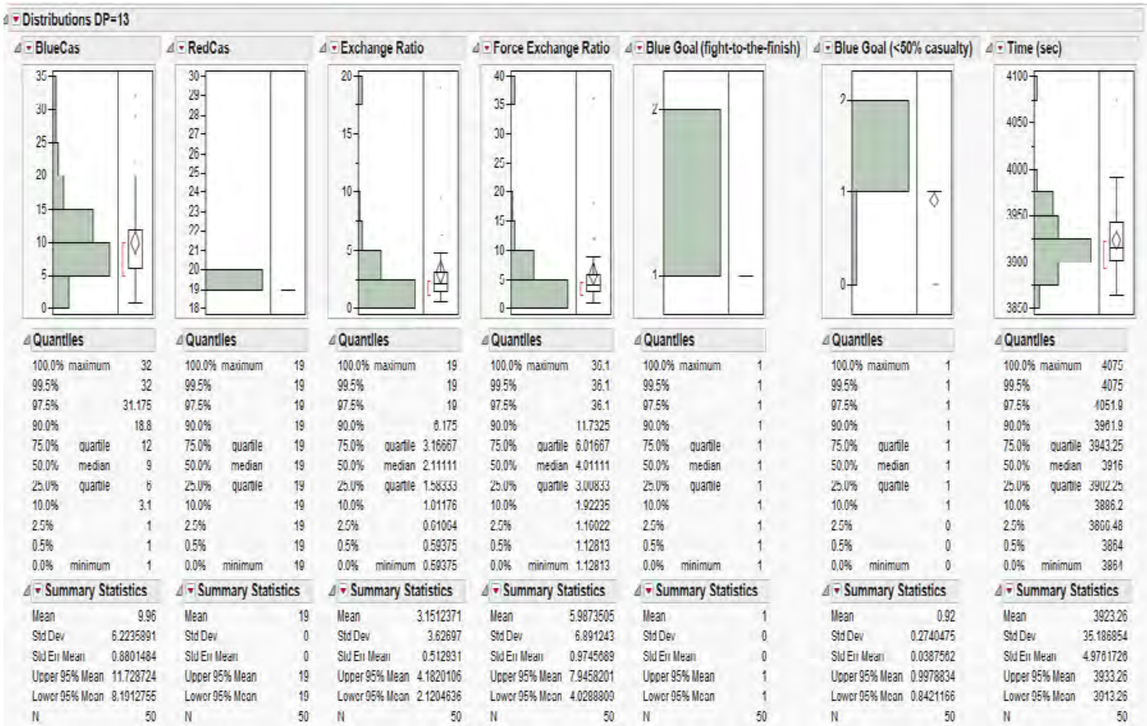


Figure 41. Distribution Plots for Design Point 13.

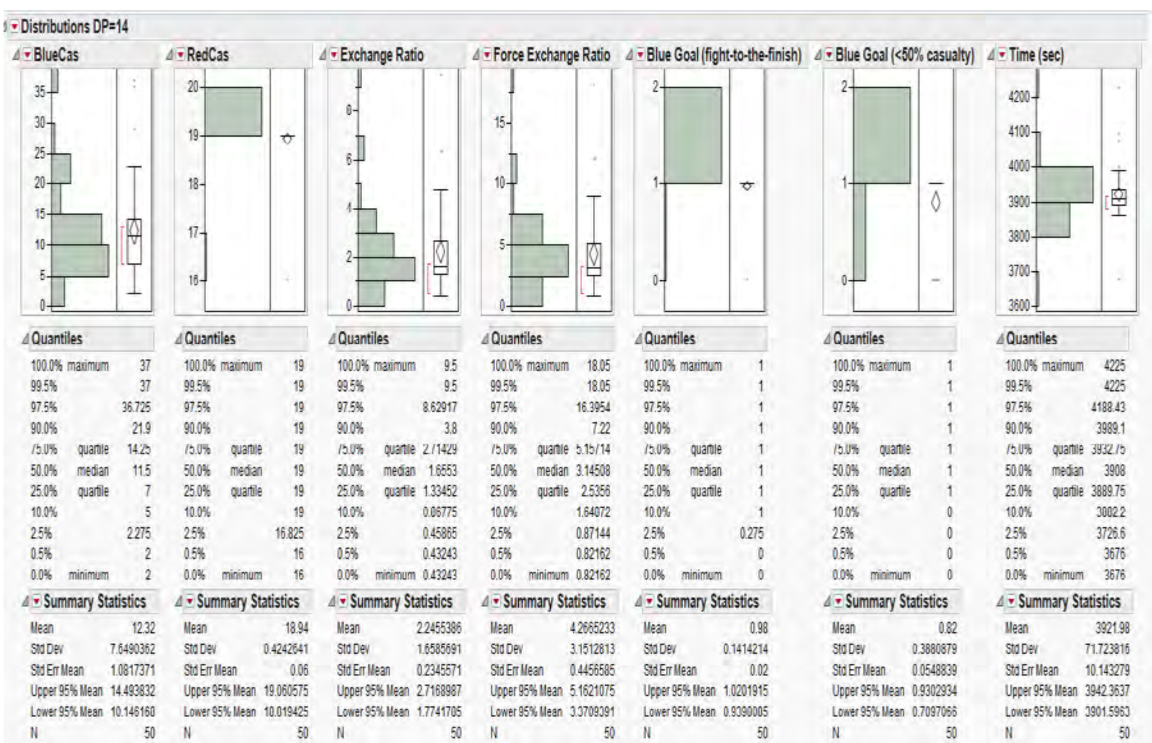


Figure 42. Distribution Plots for Design Point 14.

Figure 43. Distribution Plots for Design Point 15.

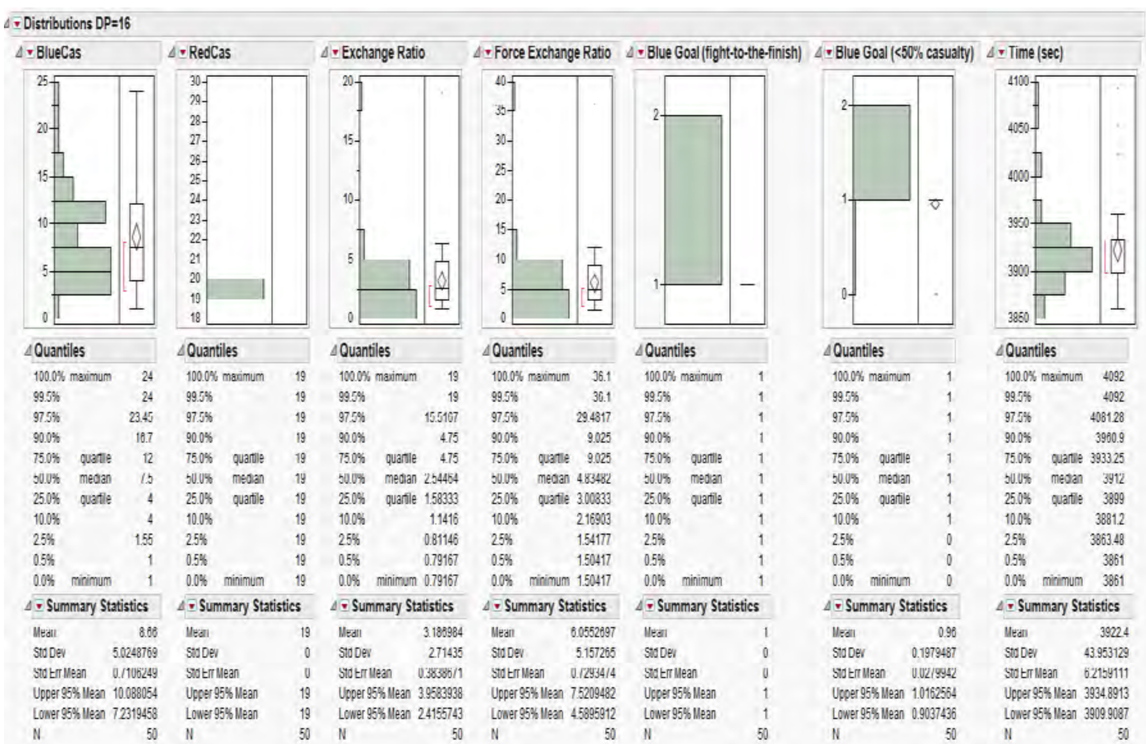


Figure 44. Distribution Plots for Design Point 16.

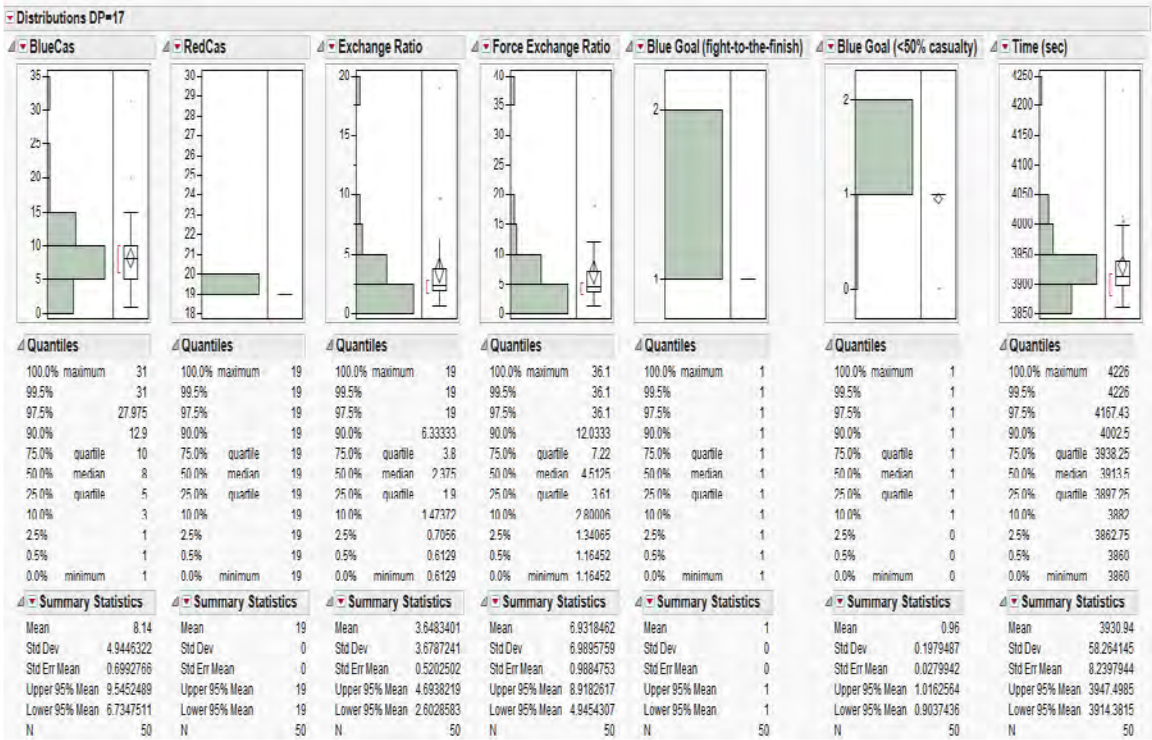


Figure 45. Distribution Plots for Design Point 17.

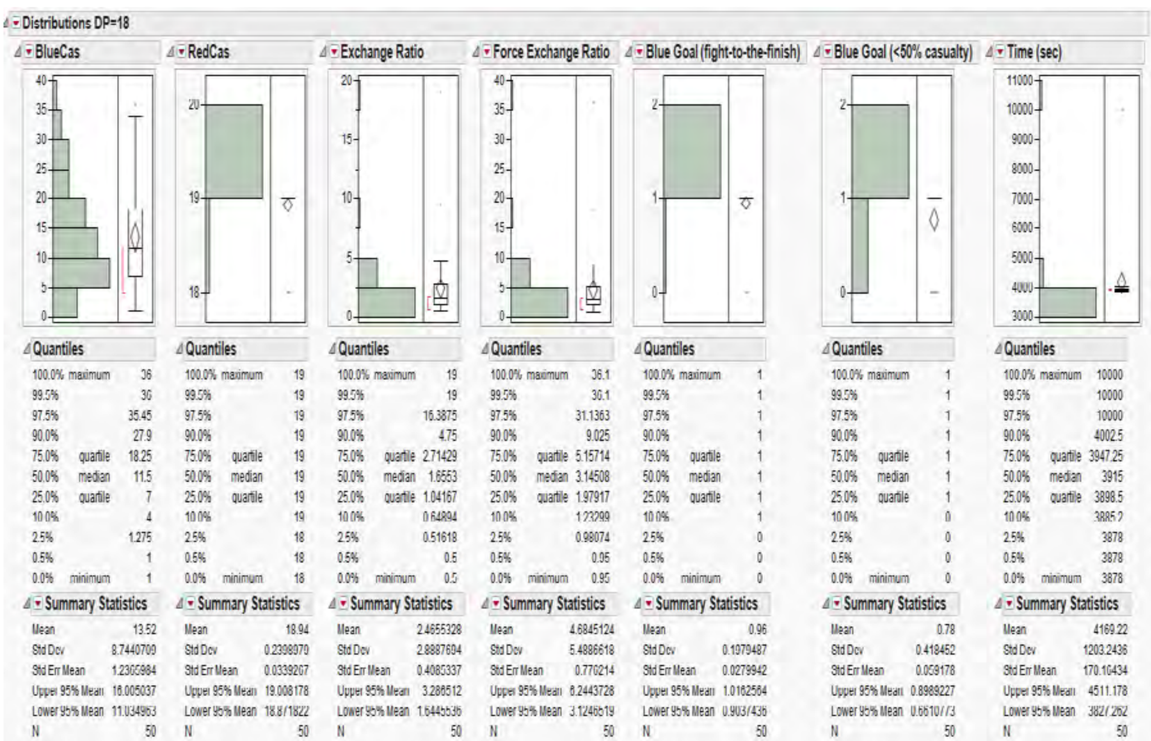


Figure 46. Distribution Plots for Design Point 18.

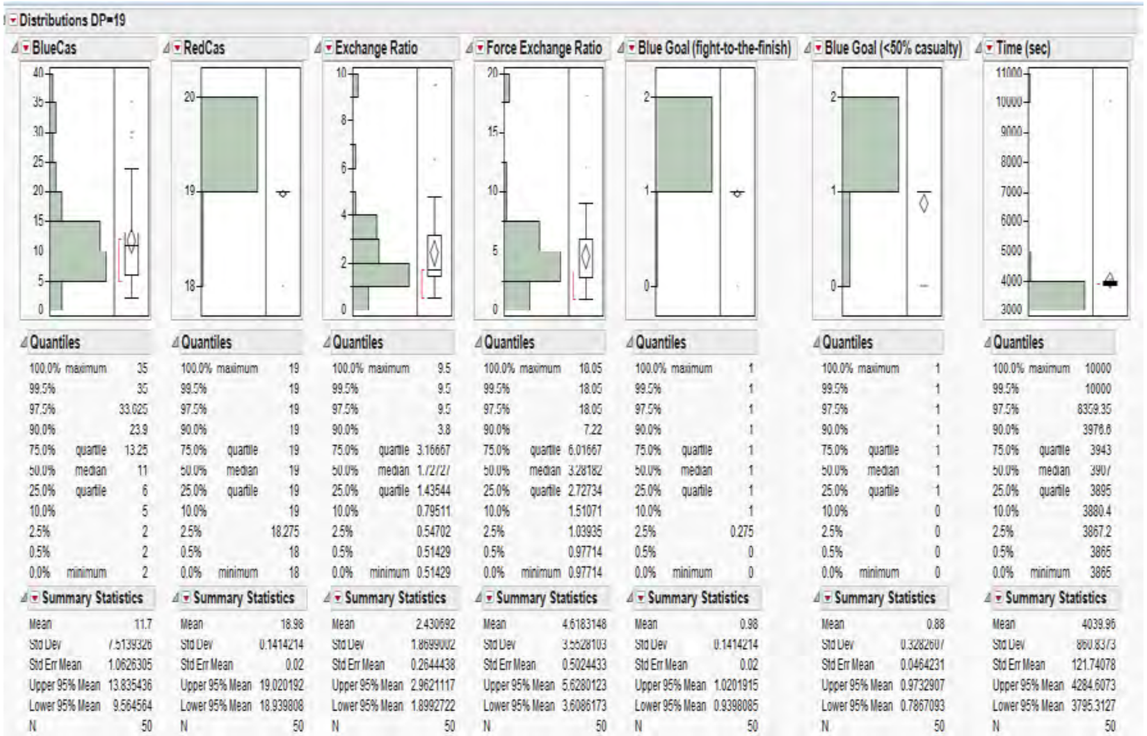


Figure 47. Distribution Plots for Design Point 19.

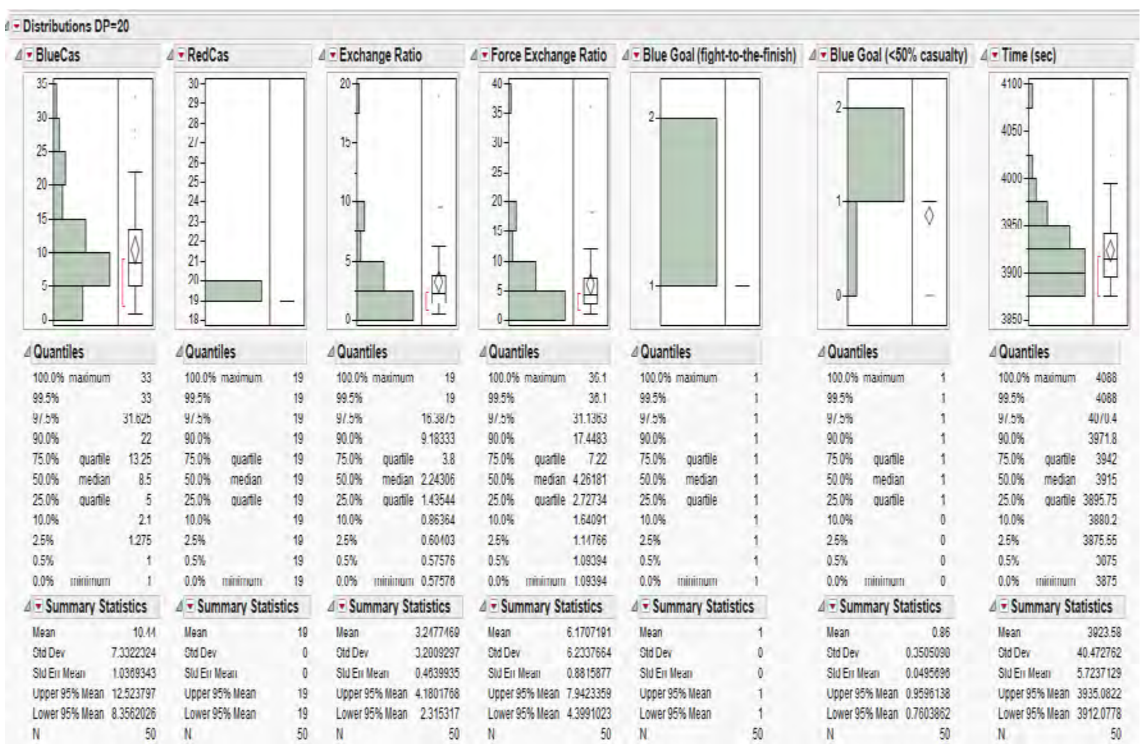


Figure 48. Distribution Plots for Design Point 20.

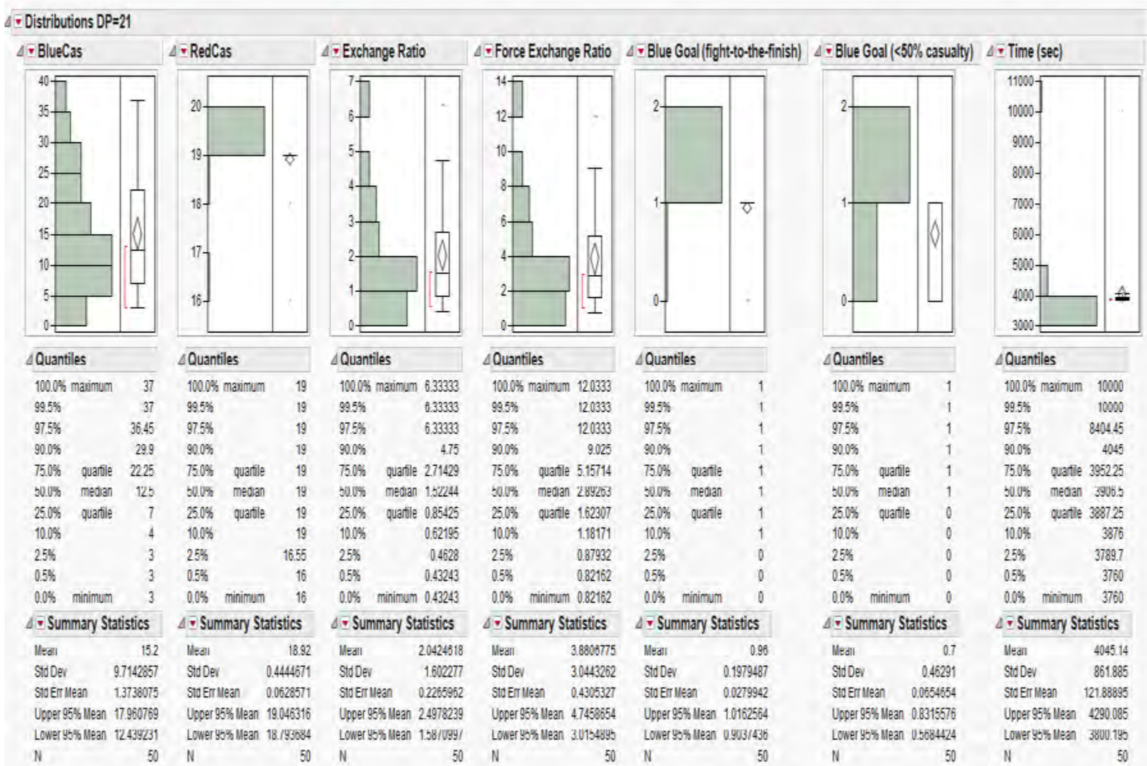


Figure 49. Distribution Plots for Design Point 21.

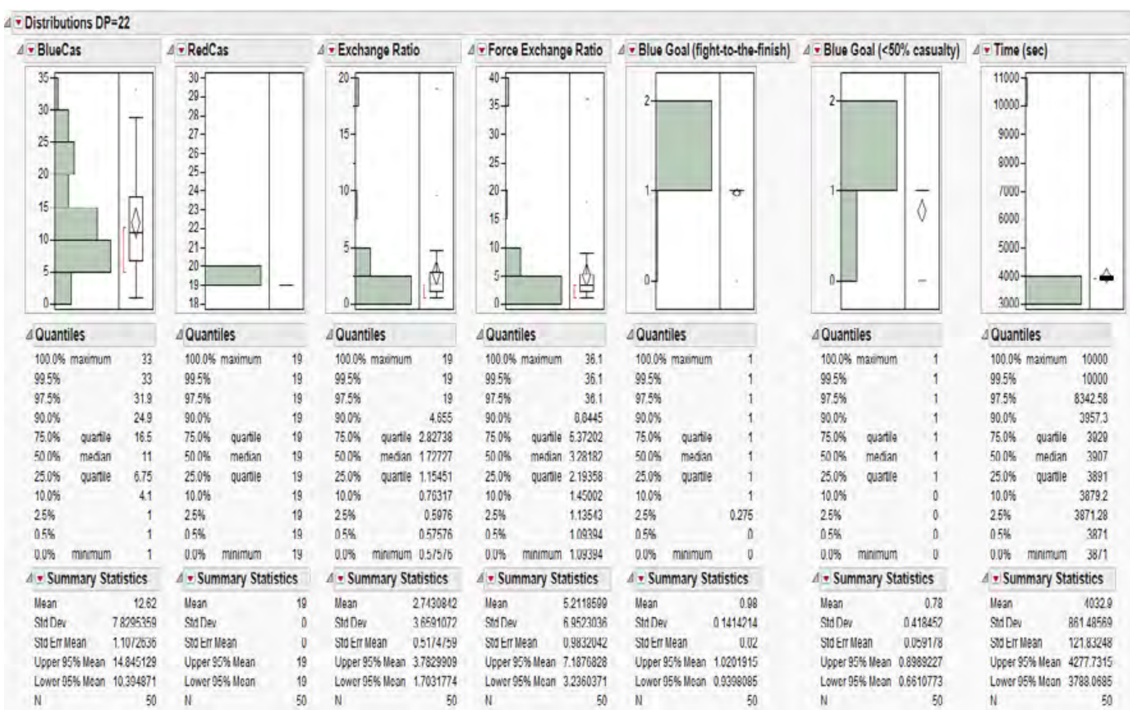


Figure 50. Distribution Plots for Design Point 22.

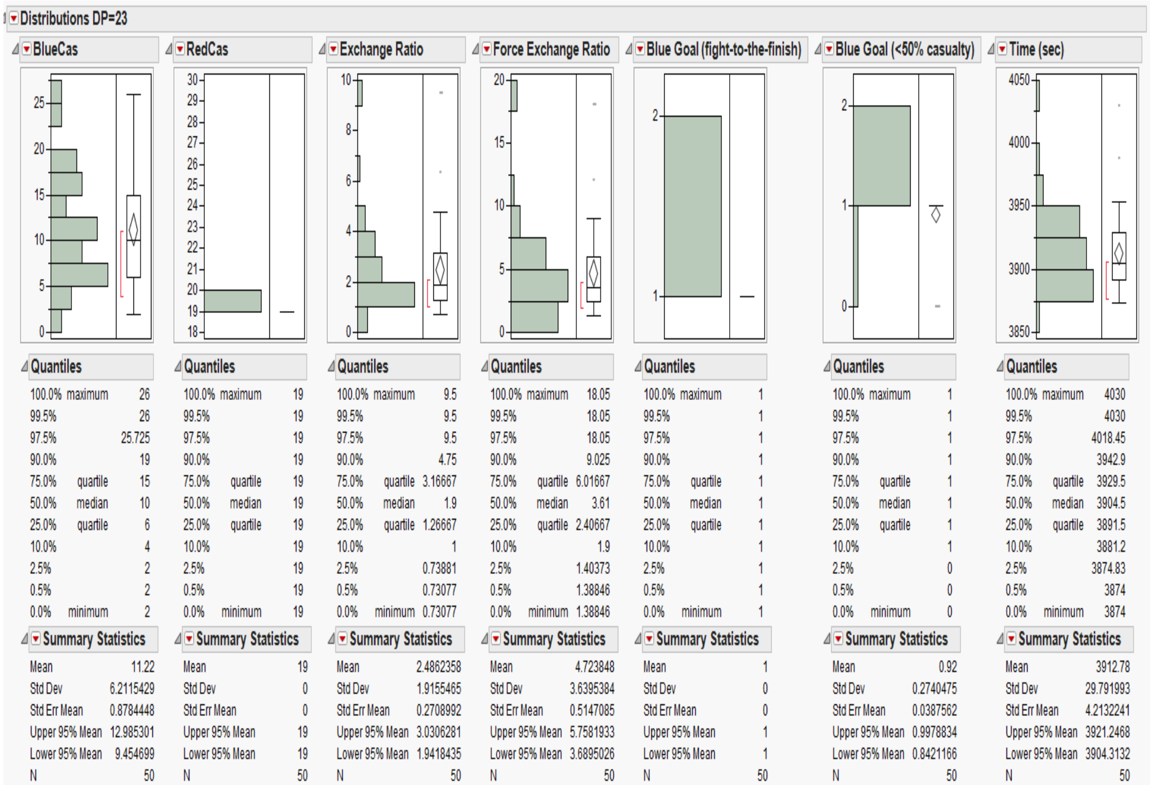


Figure 51. Distribution Plots for Design Point 23.

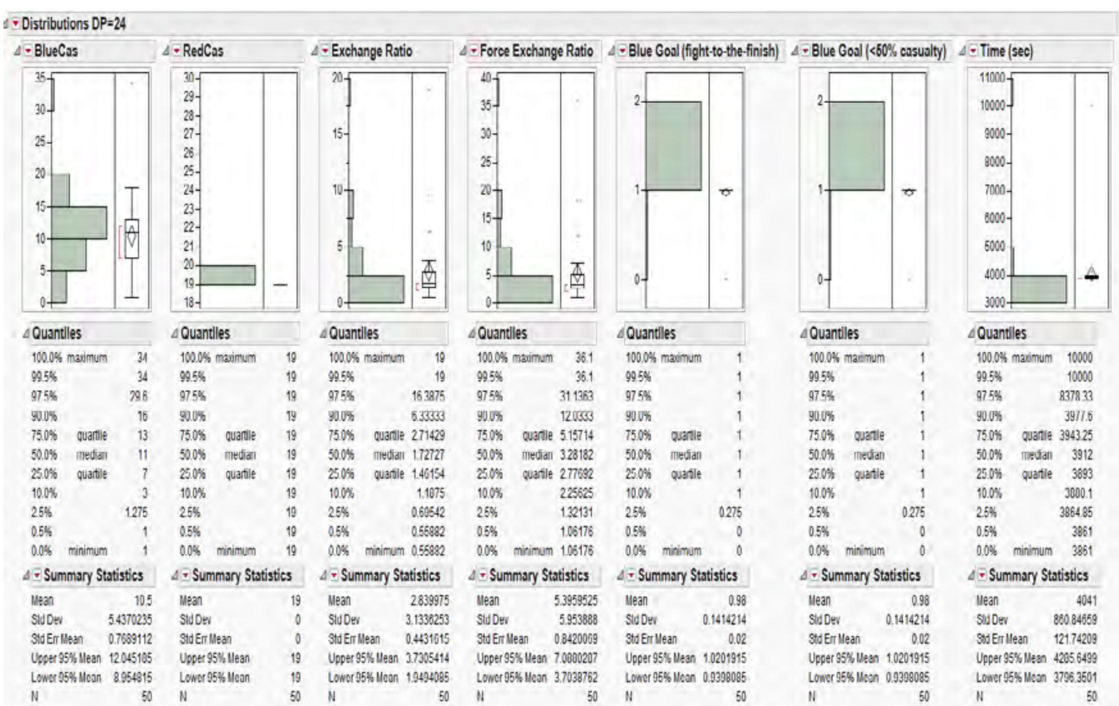


Figure 52. Distribution Plots for Design Point 24.

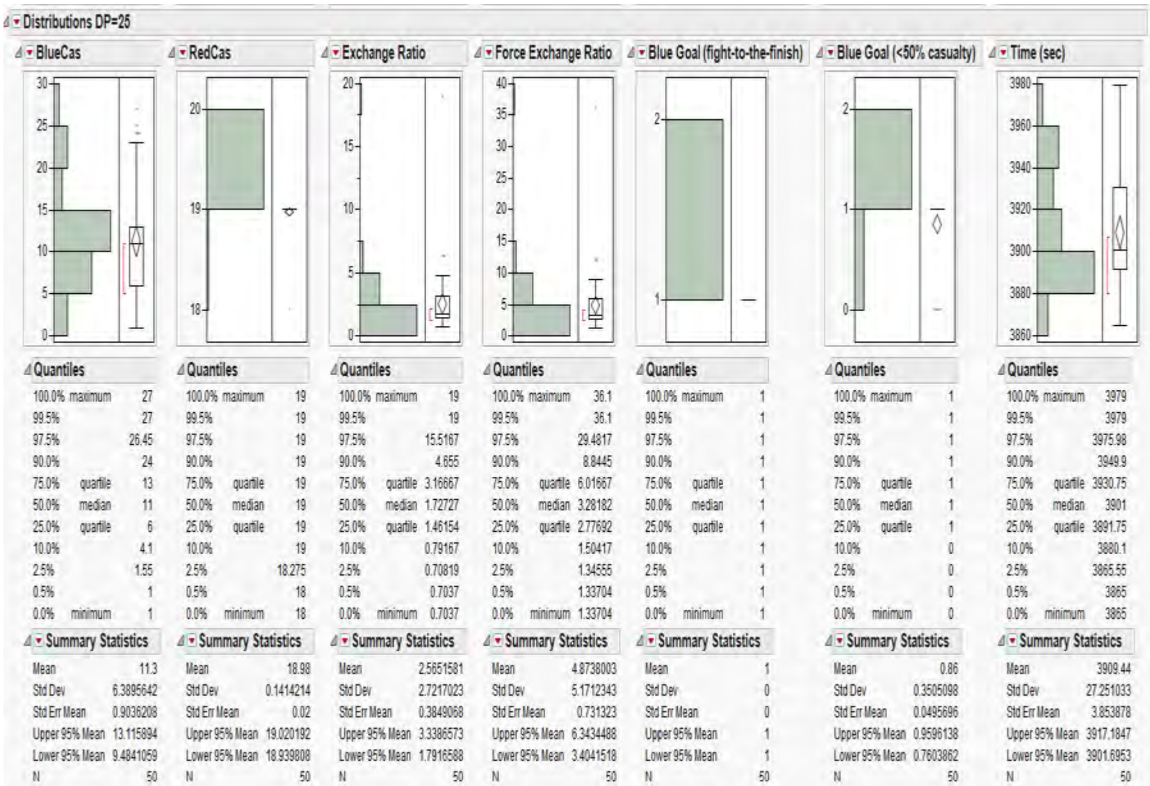


Figure 53. Distribution Plots for Design Point 25.

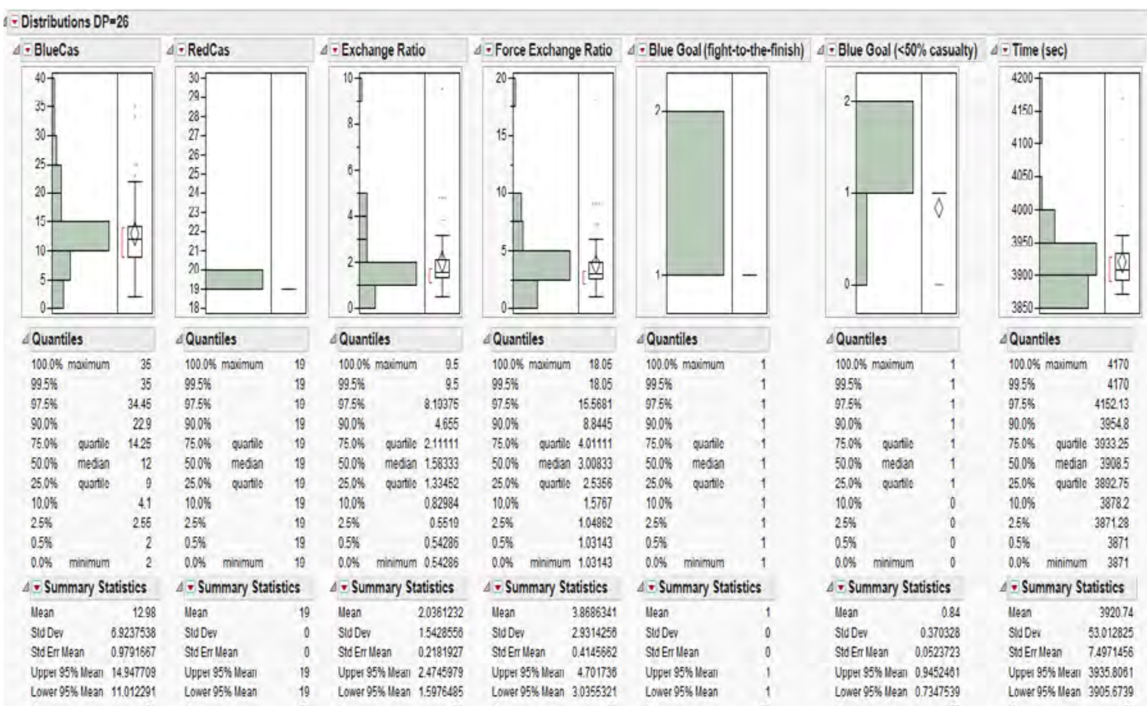


Figure 54. Distribution Plots for Design Point 26.

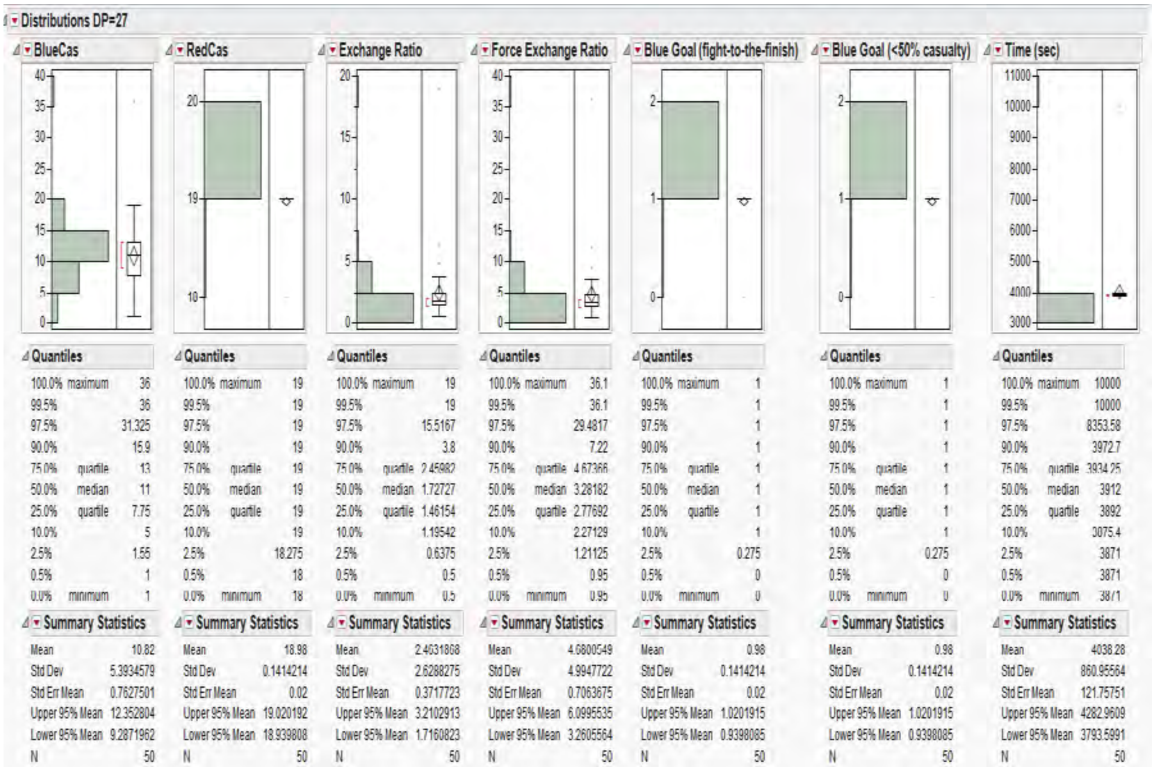


Figure 55. Distribution Plots for Design Point 27.

Figure 56. Distribution Plots for Design Point 28.

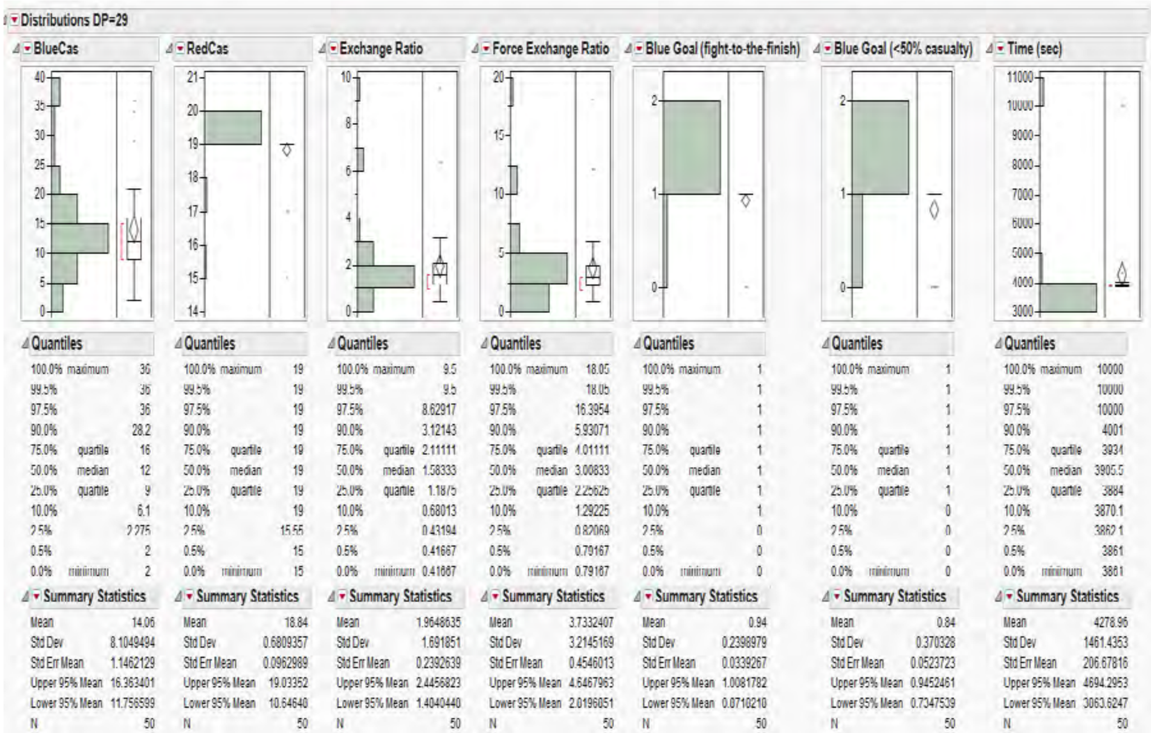


Figure 57. Distribution Plots for Design Point 29.

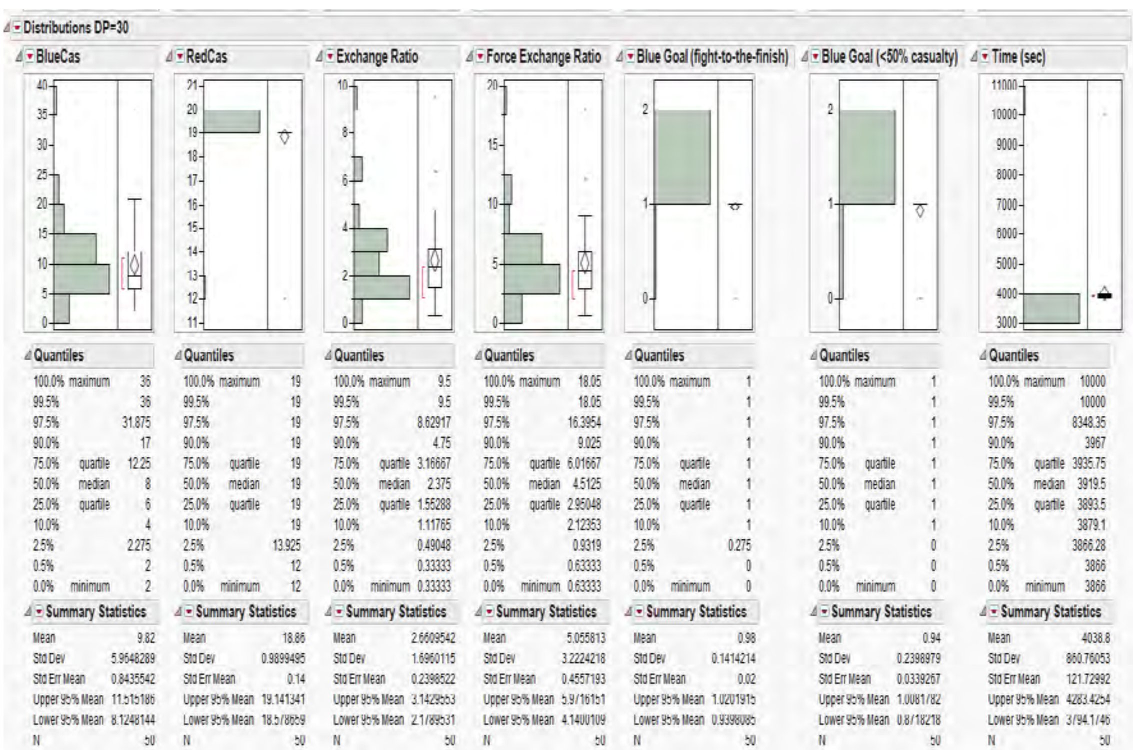


Figure 58. Distribution Plots for Design Point 30.

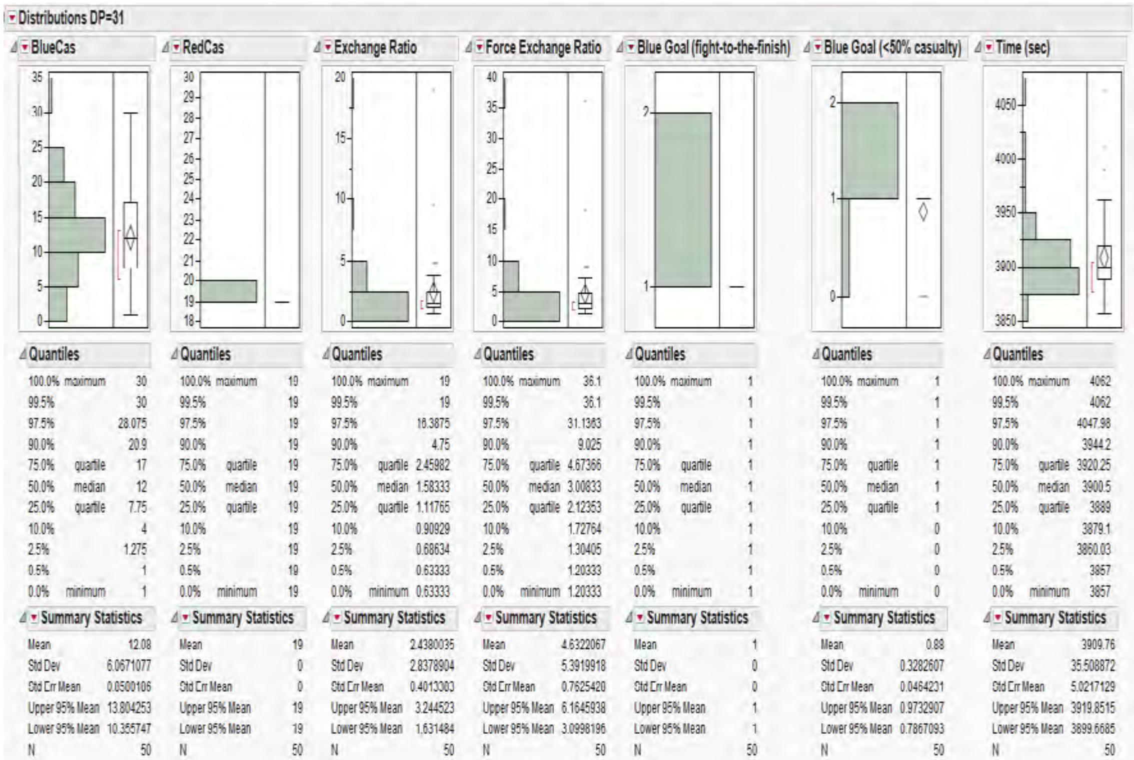


Figure 59. Distribution Plots for Design Point 31.

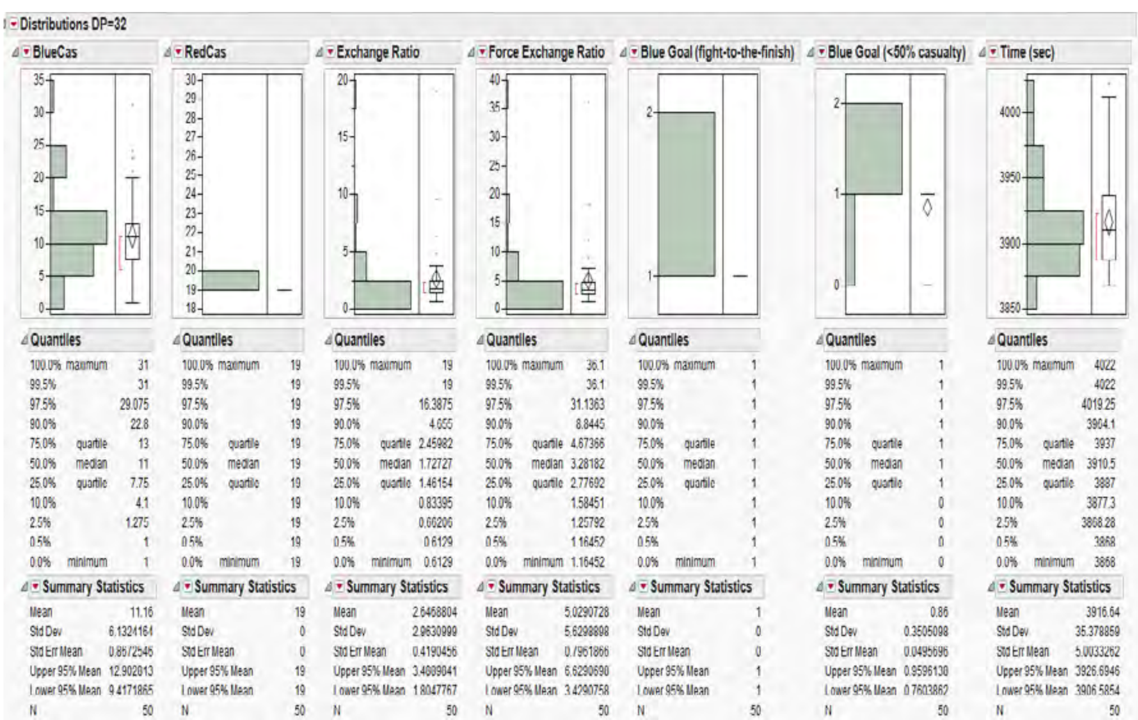


Figure 60. Distribution Plots for Design Point 32.

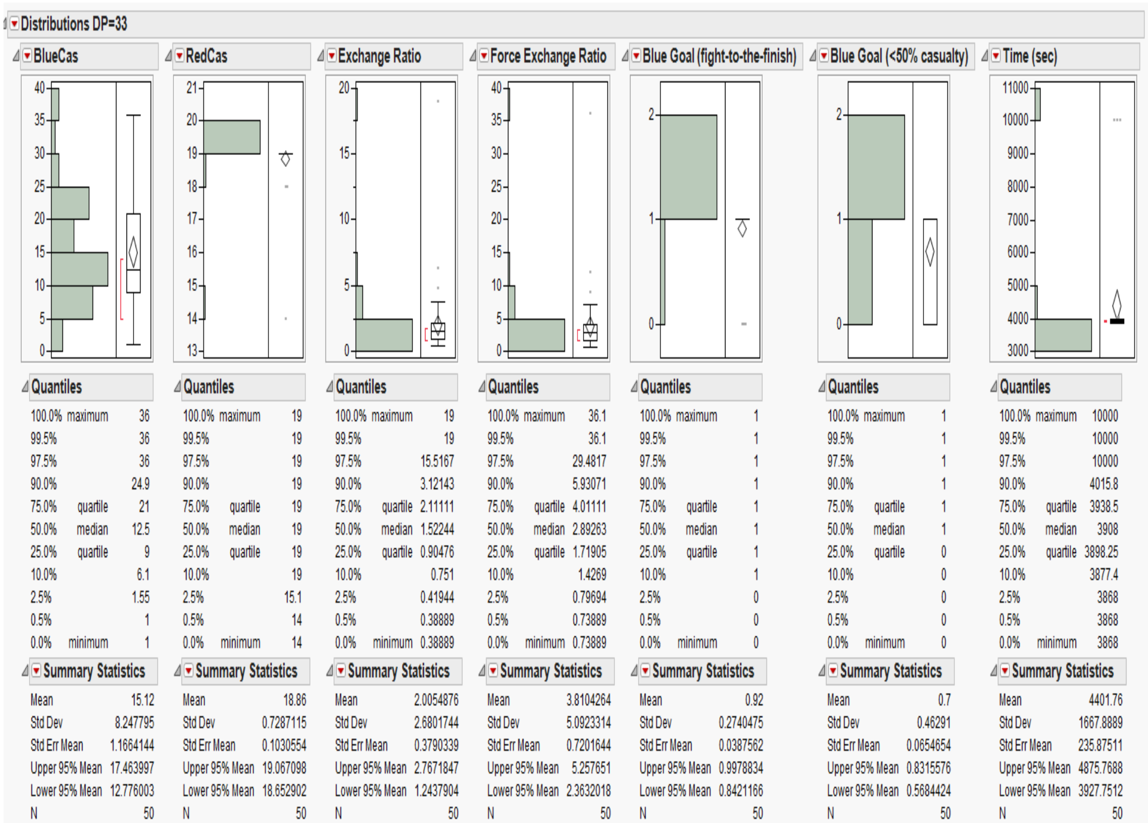


Figure 61. Distribution Plots for Design Point 33.

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